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Published by George Banta Company, Inc., Menasha, Wisconsin. Issued six times a year in February, April, June, August, October and December. Second-class postage paid at the Post Office at MENASHA, WISCONSIN, under the Act of March 3, 1879. Acceptance for mailing at the special rate of postage provided for in the Act of February 28, 1925, embodied in paragraph 4, Section 538, P. L. & R., authorized March 19, 1941. Copyright 1960 by the Society of Exploration Geophysicists.

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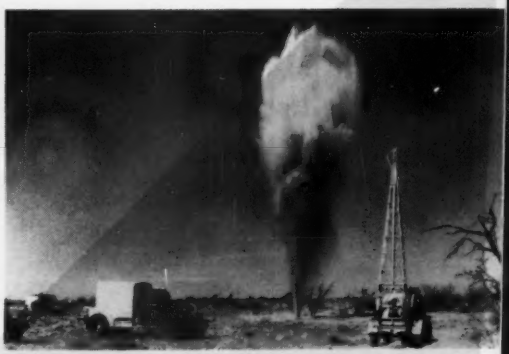

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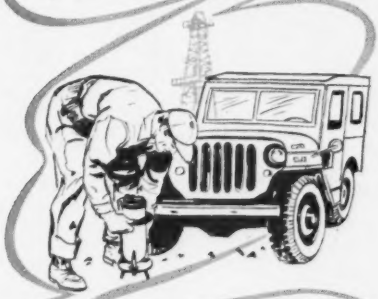

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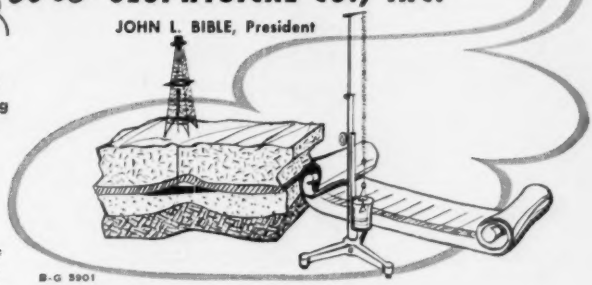

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# GEOPHYSICS

## WIDE ANGLE REFLECTIONS AND THEIR APPLICATION TO FINDING LIMESTONE STRUCTURES IN THE FOOTHILLS OF WESTERN CANADA*

T. C. RICHARDS†

ABSTRACT

Experimental and theoretical evidence is presented to show that a strong seismic event, occurring late in a record and at distances beyond the critical distance, is a wide angle reflection: and not a refraction from a high velocity limestone formation.

The evidence includes studies of the effects of anisotropy on the velocities along reflected and refracted paths and of the variation of amplitude of the event with distance. The paper also describes how the results of broadside wide angle reflection shooting may be combined with normal reflection shooting to map strongly dipping limestone structures. An application to a profile through a foothills well in Western Canada is included.

### INTRODUCTION

For over thirty years the broadside or arc refraction method has been used with great success to define buried high velocity structures with large relief. The method entails taking observations at a distance where an event, refracted from the structure, enters as the first arrival on a record, and this distance is first established by inline shooting.

In recent years, a broadside method referred to as "second event refraction" has tended to replace the first event method, its object being to make use of the "refracted" event at a distance much nearer the critical distance, and thus achieve several operational and economic advantages. This distance should be such that the event occurs a few tenths of a second later than the first onset of energy on the record and where the earlier motion has appreciably subsided. Further, from experience gained in delimiting the Mississippian limestone structures at depths of 10,000 ft or more in the eastern foothills of the Canadian Rocky Mountains, it is found that the optimum distance should be several thousand ft greater than critical in order to accommodate reasonable cross-strike depths changes, either due to dip or to faulting.

* Presented at 29th Annual Meeting, Los Angeles, November 10, 1959. Manuscript received by the Editor July 6, 1959.

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Theoretically, at increasing distances beyond critical, we should expect an increasing time separation between the refracted event and the wide angle reflected event but, almost without exception in a large number of observations in the plains and foothills, only one bold event can be followed; and this has been customarily regarded by geophysicists as a refraction because its time-distance curve appears to align with the time-distance curve of the first event refraction—see Blundun (1956).

However, Richards and Walker (1959) in discussing the resolution of the reflected and refracted events from the Mohorovicic discontinuity, gave a good record example from the Canadian foothills in front of the disturbed zone, in which the weak refracted event could be just distinguished from the much stronger and later reflected event from a limestone at a depth of about 13,000 ft. This suggests that the bold event detected elsewhere, in less favorable conditions, is a wide angle reflection.

It is necessary, however, to examine this example, and others where only the bold event is recorded, in the light of reflection theory and in some detail from physical and geometrical aspects, making use of as much velocity and depth control as may be available. The physical aspects will include measurements of (a) anisotropy since significant changes of effective overburden velocity over a wide range of angles of incidence are to be expected and (b) the variation with distance of the amplitude of the prominent second event.

The second event broadside technique is primarily adopted as a reconnaissance approach, especially in revealing faulted limestone structures, but the conventional reflection method is normally introduced later for supporting evidence and for detailing. Hitherto, each method of survey has been considered on its own merits, but by integrating the results from both methods as described in this paper, it is possible to derive information on the variations of the overburden velocity in a cross-strike direction and this in turn leads to improved structural resolution.

Figure 1 is a map of the foothills and plains area considered in this paper.

## GEOMETRICAL THEORY

Let us assume elliptical velocity anisotropy as defined by

$$T^2 = \frac{x^2}{V_x^2} + \frac{z^2}{V_z^2}, \tag{1}$$

where $T$ is the travel time between two points whose rectangular co-ordinates are 0, 0 and $x$, $z$; $V_x$ and $V_z$ are the average velocities in horizontal and vertical directions, respectively. The ratio $V_x/V_z$ is the anisotropic factor, $k$.

### *Modified Reflection Formulas*

In the case of a reflected wave, where $X$ is the distance between source and

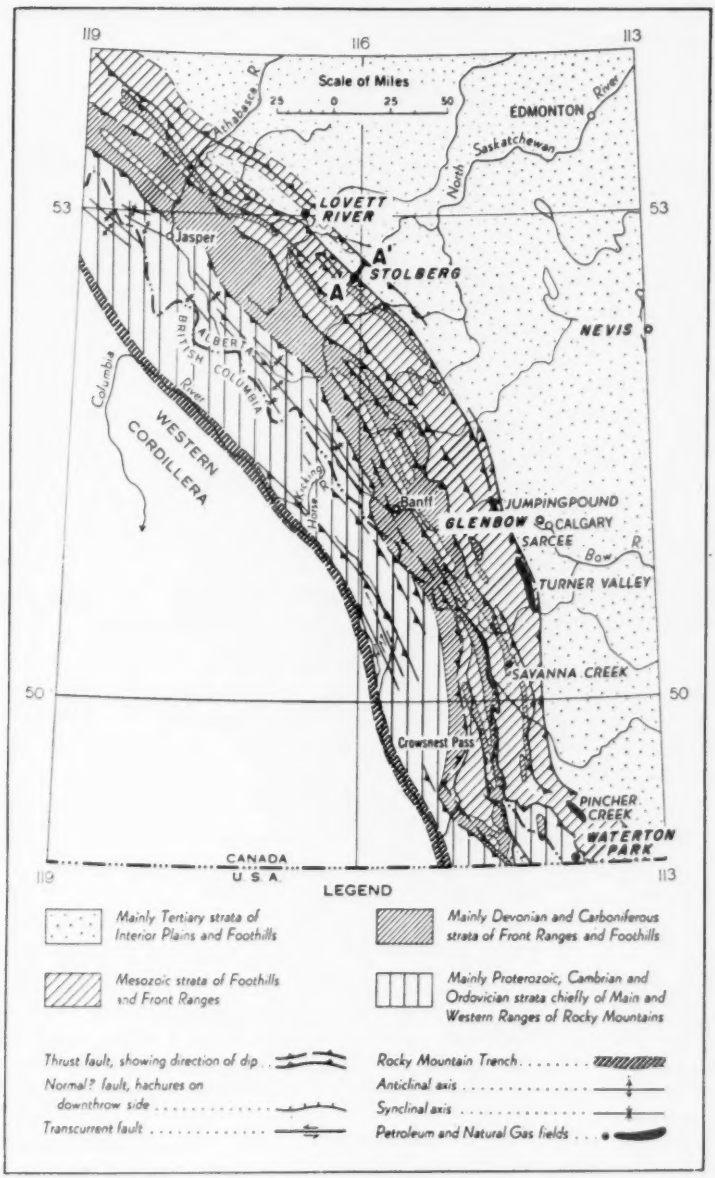


FIG. 1. Foothills limestone structures of the Canadian Rocky Mountains.

geophone and $Z$ is the depth to the reflector, it follows that the reflection time, $T_r$ is given from

$$T_r^2 = \frac{X^2 + 4k^2Z^2}{V_x^2}, \tag{2}$$

and the apparent velocity $V_a$ at any distance, $X$, in a horizontal direction, from

$$V_a^2 = V_x^2 \frac{(X^2 + 4k^2Z^2)}{X^2}. \tag{3}$$

The velocity, $V_\theta$, along the oblique path between 0, 0 and $x$, $z$ may be shown to be given from

$$V_\theta^2 = \frac{V_x^2}{k^2 \cos^2\theta + \sin^2\theta}, \tag{4}$$

where

$$\tan\theta = \frac{x}{z}.$$

*Modified Refraction Formulas*

It may be demonstrated from a consideration of Fermat's minimum time law that Snell's law, in the case of anisotropy, must be modified from

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{V_1}{V_2},$$

to

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{V_{\theta_2}}{V_{\theta_1}} \cdot \frac{V_{x_1}^2}{V_{x_2}^2}, \tag{5}$$

and from (5) we may deduce for critical refraction at an angle $\theta_c$ that

$$\tan\theta_c = \frac{kV_x}{(V_2^2 - V_x^2)^{1/2}}, \tag{6}$$

where $V_2$ is written for $V_{x_2}$ and $V_x$ for $V_{x_1}$.

It may also be shown that the modified refraction time is

$$T_R = \frac{X}{V_2} + \frac{2kZ}{V_2 V_x}(V_2^2 - V_x^2)^{1/2}. \tag{7}$$

By inspection of (7) it is clear that if $V_x$ is used in calculating depth and anisotropy is ignored, the resultant depth will be $k$ times too large; similarly, by inspection of (2), the same can be shown for reflection times.

*Correlation of Vertical Reflections with Second Events*

If the second event can be identified as a wide angle reflection from the same horizon that yields the vertical reflection, we may derive from (2) that

$$V_x^2 = \frac{X^2}{T_r^2 - T_{r,0}^2}, \tag{8}$$

where $T_{r,0}$ is the vertical reflection time. It will also be noted that

$$k = \frac{V_x}{2Z} \cdot T_{r,0}. \tag{9}$$

If, on the other hand, the second event is a refraction then, by combining (7) with (9) we find

$$V_x^2 = V_2^2\left[1 - \left(\frac{T_D}{T_{r,0}}\right)^2\right], \tag{10}$$

where $T_D$ is the refraction delay time defined by

$$T_D = T_R - \frac{X}{V_2}.$$

In the application of (8) and (9) it may easily be shown that the $V_x$ and $k$ obtained if the second event is a wide angle reflection, are both greater than they are in the case of a refraction, except, of course, if the event occurs at the critical distance when the values are both equal. If $k$, which is normally greater than unity for stratified sediments, is computed to be less than unity, then that second event identification assumed in the computation is strongly suspect.

In the application of the foregoing theory to dipping strata, the vertical direction is replaced by the direction normal to the bedding.

## EXPERIMENT I

*Measurement of the Anisotropic Factor*

Measurements of the average value of $k$ throughout the sediments overlying a high velocity refractor may be made in two ways.

*Well Geophone Method.*—The first method entails measuring the oblique travel times to a well geophone located close to the refractor, from a series of shotpoints at increasing distances from the well. It is important that the line of shotpoints lies along the regional strike and where formation dip is small, in which case the effect of varying lithology, which may be pronounced in the direction of dip, is avoided. This method and its application has been described by Uhrig and van Melle (1955).

It is clear from (1) that if, from the measurements, $T^2$ is plotted versus $x^2$, the slope of the straight line so obtained is a measure of $1/V_x^2$ and, knowing the

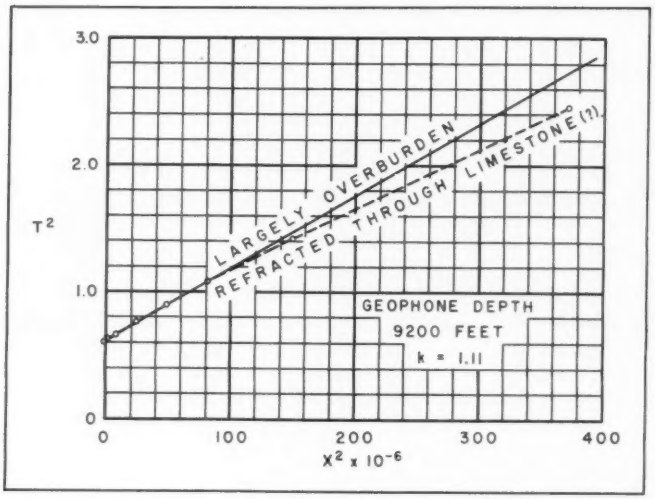


FIG. 2. Determination of $k$ at Glenbow; well survey.

velocity $V_z$ to the depth $z$, $k$ immediately follows. Figure 2 shows the results obtained in the plains area at Glenbow, where the Mississippian limestone is 9,200 ft deep, and the overburden consists largely of interbedded Cretaceous shales and sandstones. The geophone was located 20 ft within the limestone and at distances greater than 9,000 ft; the plotted values of $T^2$ suggest that the trajectories of the first events to which they refer could be influenced increasingly (a) by refractions through any contrasting velocity interfaces within the overburden and (b) through the limestone itself. With regard to (a), although the path will be longer than the direct path between geophone and shotpoint (assumed in the theory), the time taken will be less, and this becomes more marked with increasing horizontal distance.

Using the $T^2/X^2$ relationship up to a distance of 9,000 ft, the $k$ factor may be shown to be equal to 1.11.

*Reflection Method.*—The second approach makes use of the reflection travel times to a reflector near the horizon under consideration and at increasing distances from a well or point where the depth and velocity are both known. The $k$ value follows from a $T^2/X^2$ plot and the application of (2). The results in Figure 3, from which $k=1.12$, refer to an area at Nevis where the Mississippian has been eroded away, and the reflections appear to derive from the high velocity contrasting Devonian limestone at a depth of 4,800 ft.

The principle of this method is recognized to be that adopted in determining a velocity distribution with depth from a series of reflected events, as dealt with comprehensively by Dix (1955). In Dix's paper, however, it is assumed that the

velocity measured is the vertical velocity, whereas in the presence of anisotropy, it is essentially the average velocity in the direction of the bedding.

Figure 8 shows the time-distance variation of the reflections to which Figure 3 refers, and it will be noted that good agreement with the theoretical curve obtains up to a distance of 14,000 ft. Beyond 14,000 ft, interference from other events precludes the identification of the reflections with any certainty.

*Other Measurements of k.*—The well geophone method has been used for measurements along strike on a foothills structure, where a value of $k$ equal to 1.10 was found to satisfy. In this case as well as those discussed above, the overlying dominantly Cretaceous beds consist largely of shale; Figure 2 refers to a total shale content of 70 percent, Figure 3 to 70 percent and, in the case of the foothills structure, to about 60 percent.

The method of determining $k$ by utilizing the combined results given by the conventional reflection and second event times as expressed by (9), and utilizing either (8) or (10), will be discussed later but here it may be noted that in the case of the foothills structure, referred to above, the acceptable $k$ value was 1.09. In two other foothills cases where the depths and vertical velocities to the Mississippian limestone were also known, the values were 1.08 and 1.06, the shale content being about 60 percent, in both cases.

Cholet and Richard (1954), using the well geophone method, found an average $k$ of 1.09 for clays and sands (percentage unspecified) in the Sahara desert

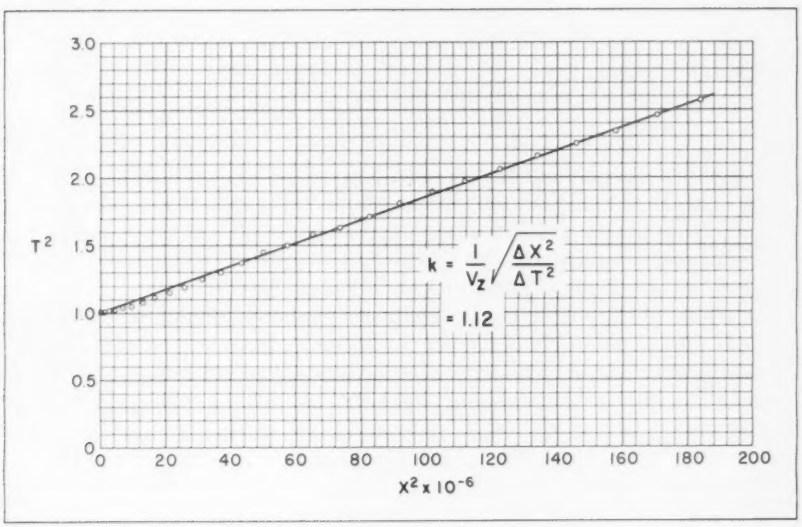


FIG. 3. Determination of $k$ at Nevis; reflection survey.

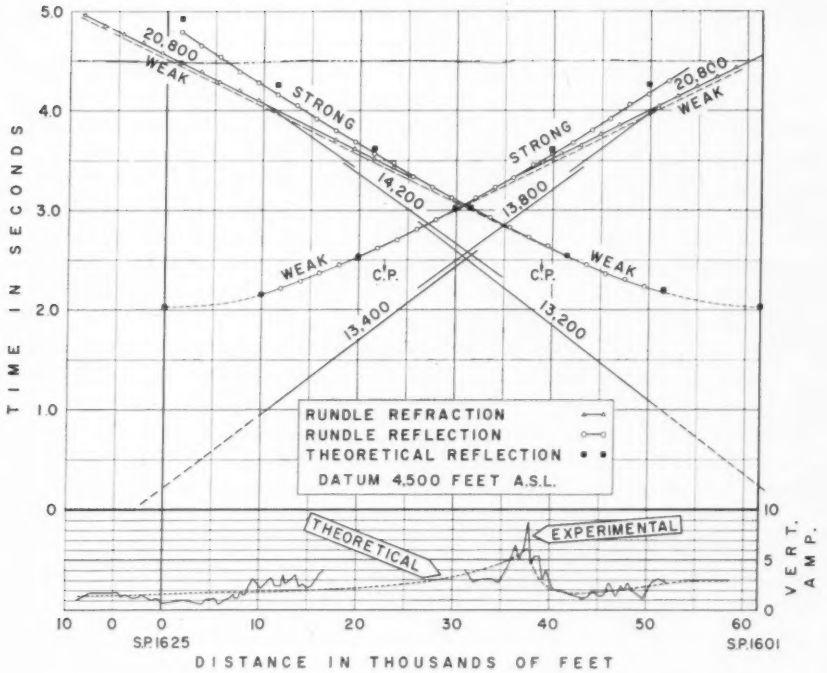


FIG. 4. Time-distance curves of Inline Study No. 1; Experimental and theoretical vertical amplitudes of Rundle (Mississippian) limestone reflection from S.P. 1601.

and 1.14 if the clays alone were considered. Uhrig and van Melle (1955) give 1.14 to 1.18 for the Pierre Shale in Colorado.

It thus appears that in a general application of anisotropy to the foothills area where the limestone overburden is less shaly, than it is in the plains, a value of $k$ of about 1.08 should be introduced into any problem connected with the consideration of velocities along paths of varying slopes.

We now critically examine the results of two detailed inline observations in Western Alberta where the geological conditions are relatively simple. The first inline proved remarkably informative in throwing light on the much debated question as to the relative amounts of reflected and refracted energy beyond the critical angle.

## EXPERIMENT II

### *Inline Study No. 1*

Figure 4 shows the time distance plots of the prominent events observed in opposite directions along a strike line some six miles in front of the disturbed foothills belt at Stolberg.

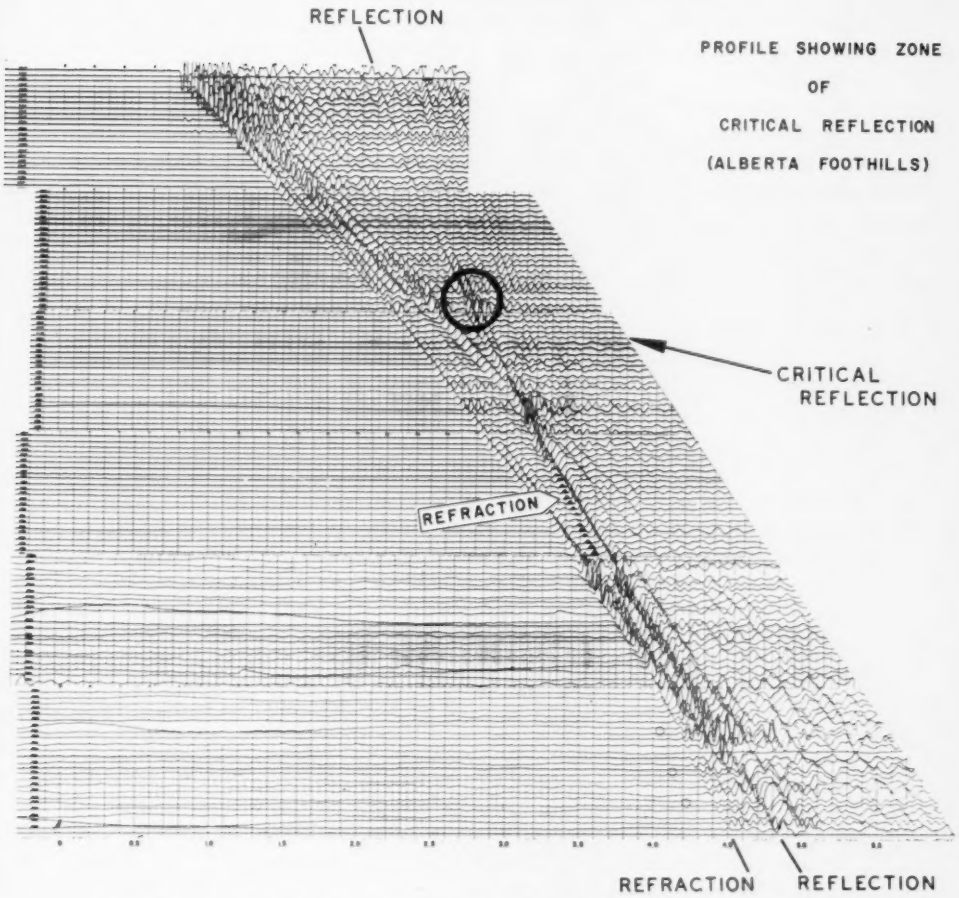


FIG. 5. Seismograms for Inline Study No. 1, (S.P. 1601); total spread 17,450 to 61,850 ft; charge sizes 30, 50, 100, 150, 150, 175 lbs reading from the top; amplifier gains all 6 db.

Observations were carried to 60,000 ft in one direction and to 70,000 ft in the other, both starting at 10,000 ft. The instrumentation, which remained uniform throughout, included 2 cps refraction geophones and low frequency amplifiers with no A.V.C. and no suppression. Geophones were located at 400-ft intervals with a two-geophone overlap at the end of each spread. (In the figure, times are plotted at intervals of 2,000 ft only).

*Analysis.*—The time-distance curves are almost identical in the two directions of shooting, the true limestone velocity from the first event observations being 20,800 ft/sec. A series of records from one of these lines is shown in Figure

5 and the first movement of the event marked "reflection" gives a time plot which is characteristically that of a reflected wave in the range 10,000 to 30,000 ft as may be shown by the linearity of a $T^2/X^2$ plot.

If we now extend the $T^2/X^2$ line towards the origin, we find that $T^2=4.100$ or $T=2.024$ sec, which should correspond to the vertical reflection time to the limestone. From the slope of the $T^2/X^2$ curve, we find that $V_z=13{,}360$ ft/sec and, assuming that $k=1.08$, $V_z=12{,}380$ ft/sec. Consequently, the depth, $Z$, to the limestone is 12,520 ft and this is in good agreement with the value established from a conventional reflection survey which tied this origin at S.P. 1601 (see Figure 4) to a well in the undisturbed zone in front of the foothills.

The critical distance $2Z \tan \theta_c$ obtained by using equation (6) becomes 22,800 ft, but it is seen that the time plot through the limestone first and second events is not tangential to the reflection curve at the critical distance. This is not surprising as the amplitude of the refracted events plotted, measured from first maximum to first minimum, is only of the order of a two or three mm, and the precise onset, bearing in mind that, theoretically, the refracted event in contrast to the reflected event must have a much slower "build up," could well be earlier than measured. Moreover, if the refracted event be reasonably assumed to enter about half a wave length or 0.040 sec earlier, the tangential condition would be satisfied, as illustrated in Figure 4. The greater theoretical reflected times at distances beyond 30,000 ft could be attributed to our two-layer assumption in computation, as discussed above.

*Experimental Reflection Amplitudes.*—One of the most important criteria for identifying a reflection event is the theoretically large increase in amplitude at the critical distance. This is well recognized, especially in the new techniques for measurements of the crustal thickness from explosive sources, but so far no systematic study of the variation of this amplitude with distance has appeared in the geophysical literature. The controlled shooting of the inline under consideration makes this possible and the results are shown in Figure 4 in the case of shooting from SP 1601, the records for which are those in Figure 5.

The amplitudes have been measured from first maximum to first minimum and reduced to an arbitrary datum by adjustments of the repeat geophone measurements at the beginnings and ends of neighboring spreads. In this way all effects due to changes in size of charge and shot hole conditions are eliminated.

For certain distance ranges beyond the critical distance, the reflection amplitudes have obviously suffered interference from other advancing events and such amplitudes have not been plotted. Those amplitudes plotted are reasonably clear of important background interference and the erratic nature of the curves is attributed largely to changes in geophone "placement" and to possible changes in geophone-amplifier sensitivities. The curve shows a pronounced maximum in the neighborhood of the critical distance and high amplitudes for several thousand ft beyond.

*Theoretical Reflection Amplitudes.*—We must now see how nearly this experi-

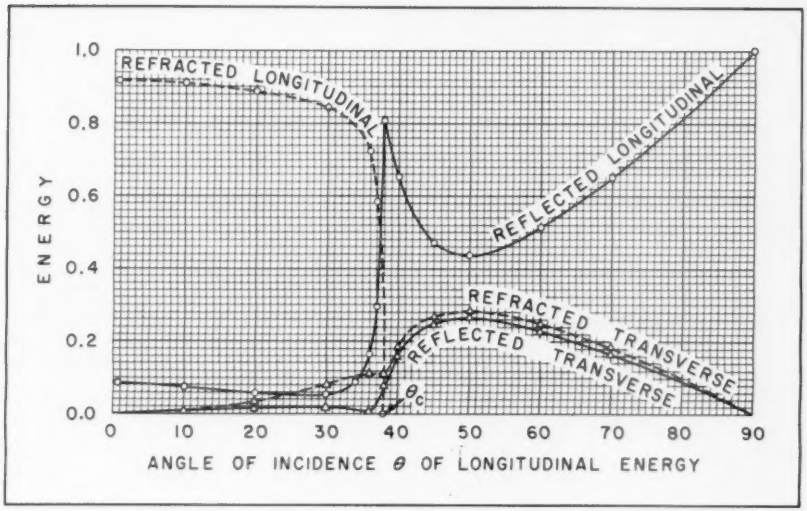


FIG. 6. Theoretical energy distribution for longitudinal plane waves incident on limestone;
$v_1 = 12{,}800$ ft/sec, $\rho_1 = 2.40$
$v_2 = 21{,}000$ ft/sec, $\rho_2 = 2.65$

mental variation of vertical amplitude with distance agrees with theoretical expectation. Assuming plane wave theory, we first compute the partition of incident longitudinal energy into reflected and refracted components both in the longitudinal and transverse types, using the equations developed by Knott (1899) or Muskat (1940).

In his paper, Muskat considers a series of velocity and density contrasts but only carries his computations for angles of incidence from 0 to 30 degrees. It is, therefore, necessary to extend the calculations up to and beyond the critical angle, and this was expeditiously carried out with the digital computer. The limestone was assigned a longitudinal velocity of 21,000 ft/sec and a density of 2.65; corresponding figures for the overburden were 12,800 ft/sec and 2.4. Although the overburden velocity varies with the angle of incidence, its variation is not sufficient to affect the shape of the curves to any important extent and the velocity along the critical direction has been assumed to apply at all angles of incidence. The ratio of longitudinal to transverse velocities has been taken to be 7/4. The results are shown in Figure 6, in which the characteristic minimum in the reflected longitudinal energy, complementary to the combined energies in the reflected and refracted transverse components beyond the critical angle, is well developed.

In the case of the longitudinal reflected wave, amplitudes are proportional to

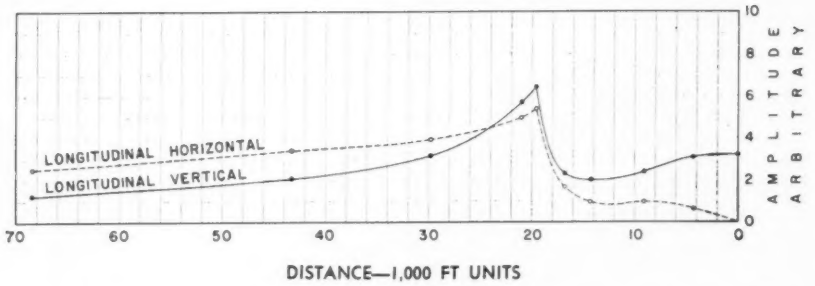


FIG. 7. Theoretical variation of reflected longitudinal amplitudes at ground surface with distance.

the square roots of the energy values but we must correct these amplitudes for the spread factor and for the behavior of the reflected wave on arrival at the surface of the ground. It may easily be shown that the spread factor is given by the inverse of the total distance travelled by the wave while Jeffries (1926) provides tables for the vertical and horizontal components of amplitude of the wave at varying angles of emergence.

The corrected amplitude components plotted against distance are shown in Figure 7 and the curve corresponding to the longitudinal vertical amplitude is also shown superposed and matched at the peak value in Figure 4. Very good agreement is seen to exist.

Any departures between the two curves may be attributed to (a) experimental error, (b) the assumption that the problem is a simple two-layer one whereas it is known that the limestone overburden may be divided into certain discrete velocity beds involving secondary reflections and refractions, (c) the neglect of energy absorption or scattering, (d) the neglect of the energy required in the generation of the refracted wave at critical incidence, and (e) the neglect of curvature of the wave front. It appears that all the above factors are of second order magnitude. The refraction amplitudes both in the first and second events are seen to be relatively small in Figure 5. Unfortunately, it is not possible to consider the variation of the amplitudes of the first events with distance in the light of head wave theory, as the distance range is not large enough nor may the amplitude be measured with the necessary precision. It is perhaps pertinent to note that Levin and Hibbard (1955) in model experiments have shown that the amplitude of the wide angle reflection is much greater than that of the first event refraction.

*Horizontal Amplitudes.*—In Figure 7, the horizontal amplitudes of the longitudinal motion of the ground are both appreciable from distances just before critical to distances much greater than critical; and in the second event range of observation from critical to critical plus 15,000 ft (say), they are even greater than the vertical amplitudes. This has an important practical significance, for

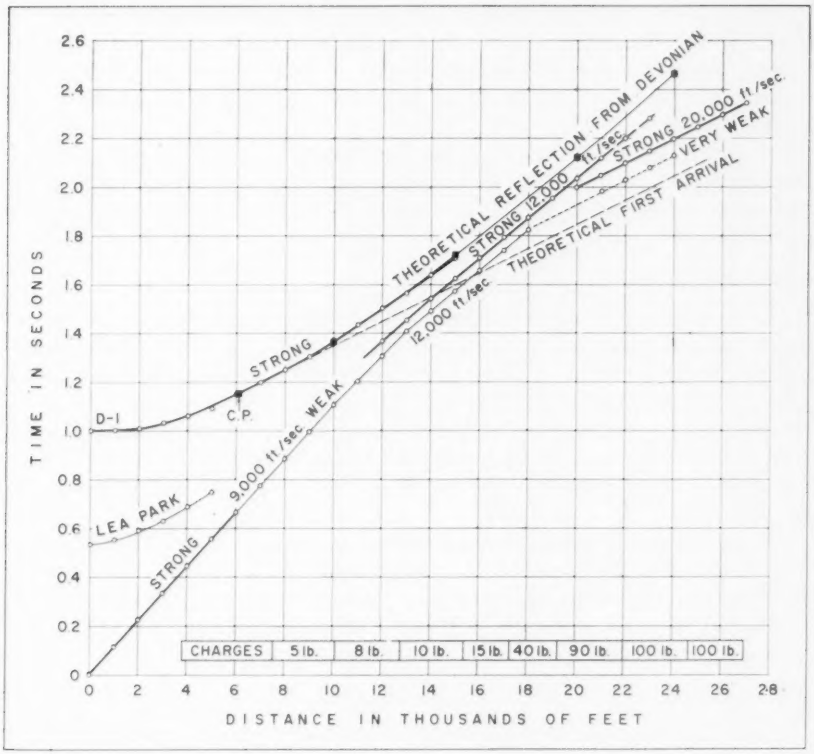


FIG. 8. Time-distance curve of Inline Study No. 2.

it would appear that a horizontal geophone would be most informative in the second event range. Although other horizontal motion might obscure the two reflected events, an experimental investigation appears to be worth while. Fortunately, low velocity weathering is not important in the foothills of Western Canada so that the angles of emergence of the respective waves should not depart greatly from those theoretically implied.

*Inline Study No. 2*

Figure 8 shows the time-distance plots of reflections and refractions from the Devonian limestone, as referred to in the construction of Figure 3. The shooting involved close correlation at intervals of 400 ft from the shotpoint to a distance of 30,000 ft with a one geophone station overlap between spreads, but only times at 1,000 ft intervals are plotted in the figure.

The theoretical critical distance is 6,100 ft, but no refracted events can be identified until weak first arrivals enter at 21,000 ft with a velocity of 20,000 ft/sec. Earlier onsets, as in the case of Figure 4, are not discernible at predicted theoretical times and this is doubtless because the charges of 40 and 90 lbs are quite inadequate.

In the experimental work along this line, reflection equipment was used, and the time lag effects introduced by adding extra stages of filtering were suitably corrected for. Because of these filter changes, no amplitude studies, such as those for Inline 1, were made.

*Other Inline Studies*

In shooting second event inlines in the foothills or plains in order to tie second event broadsides, it is customary to confine observations to spreads extending from about 10,000 to 20,000 ft and embracing the broadside distance; and a series of such spreads, each tying with its neighbor, is obtained by moving the shotpoint by the length of spread. A long inline, shot in reverse, is covered in this way, but difficulties are encountered when attempts are made to match the apparent velocities registered in the two directions, on the assumption the events are refracted.

From a study of several inlines observed by this method we find that, in almost every case, the apparent velocity decreases with distance irrespective of the direction of shooting. This result also holds when any one spread is observed at different distances from two shotpoints, so that once again we have strong supporting evidence that the second event is in reality a wide angle reflection.

## EXPERIMENT III

Thus far, in almost ideal geological conditions, we have demonstrated that, at second event distances beyond the critical angle, the wide angle reflection carries considerably more energy than the refraction. In disturbed geological conditions, however, only one second event is detectable and before assuming that this is a wide angle reflection, we must eliminate any possibility that the event could be a refraction. This has been done in several foothills studies, but here we shall confine our attention to the seismic results of conventional reflection shooting and second event broadside along a cross-profile through the Triad B.A. et al No. 1 well at Stolberg, where the depth and vertical velocity to the Mississippian limestone are known.

*Geology*

A geological section through the well, incorporating the results of drilling, is shown in Figure 9. To the southwest and some 20 miles beyond the limit of the section, the front ranges of the Rocky Mountain terminate in the McConnell thrust where beds of Cambrian and Proterozoic age come to the surface. To the northeast of this thrust, mainly Mesozoic strata are encountered at the surface in a series of thrust faults, mostly with southwesterly dips. Within the late Meso-

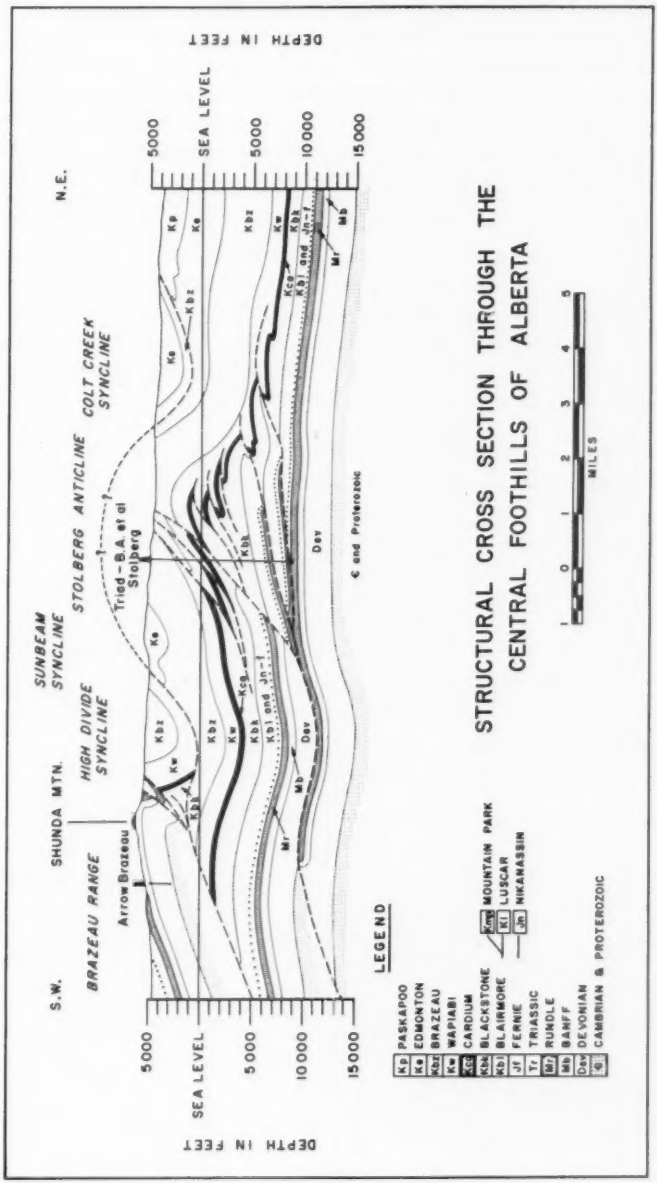


FIG. 9. Geological cross-section at Stolberg; Rundle limestone is shown with vertical shading (from Guide Book, Nordegg, 1958: Alberta Society of Petroleum Geologists).

zoic, the faults hade at relatively small angles, but deep in the section there is a tendency to fault convergence so that the more competent Palaeozoic beds are displaced on fewer thrusts.

In places the Palaeozoics are thrust to the surface to form ranges, e.g. the Brazeau Range and Shunda Mountain, while at depth they may be thrust into a series of overriding sheets, or slices, each of which may enjoy culmination, terminated by faults, as illustrated in the figure.

*Seismic Layout*

At Stolberg a faulted anticline is clearly revealed in surface exposures, but the disposition of the Rundle limestone at depth could only be predicted geologically within wide limits. In the seismic approach to afford better definition, first event two-way observations made along a strike direction to the southwest of the surface axis, shows that the true velocity of the limestone was 21,000 ft/sec, while the effective overburden velocity appeared to lie between 13,000 and 14,000 ft/sec. The effective first event distance was at least 65,000 ft and the depth was computed to be between 11,000 and 12,000 ft.

From these parameters, the critical distance appeared to be about 20,000 ft, and in order to register the limestone "refraction" as a second event a few tenths of a second later than the first motion on the record, a distance of about 30,000 ft was considered appropriate.

Broadside shooting, similar to the procedure described by Blundun (1956) followed from a series of shotpoints, each into 50 percent overlapping spreads of 24 geophones, 400 ft apart. The mid-point profile of one such broadside pattern coincides with the line of section through the Stolberg well. A conventional reflection survey using split spreads with a shotpoint interval of 1,320 ft, was run along this line of section.

*Analysis of Reflections and Second Events*

We first construct a one-way reflection time migration section as described by Rice (1953) and draw the time phantom at the Mississippian level in the well, as shown schematically in Figure 10. Let $A$ be the position of a shotpoint, the normal from which meets the limestone at $Q$ in the well. Now the time, $t$, between $A$ and $P$ in the time triangle $APQ$ refers to a distance, $vt$, where $v$ is the horizontal velocity between $A$ and $P$, which in the foothills is fairly uniform at 10,000 ft/sec.

The distance corresponding to the time $AQ$ is, therefore, given by

$$N = \sqrt{(vt)^2 + H^2}, \tag{11}$$

where $H$ = depth to the limestone at $Q$.

Substituting (11) in (9) where $N$ is written for $Z$, we obtain

$$k = \frac{V_x \cdot T_{r,0}}{2\sqrt{(vt)^2 + H^2}}. \tag{12}$$

We next consider the second event time, $T_r$ or $T_R$ at a distance, $X$, and corresponding to a strike path whose mid-point is at $A$, and apply (8) and (10) in turn. Two values of $V_x$ are obtained and, by substituting in (12) we find two values of $k$. If it is found that $k$ is unrealistic, then the assumption made regarding the nature of the second event in computing it, is suspect.

Normal one-way reflection times from any other points such as $B$ and $C$ in Figure 10 may now be scaled off and, combining these times with the corresponding second event broadside times, further values of $V_x$ obtained. These are con-

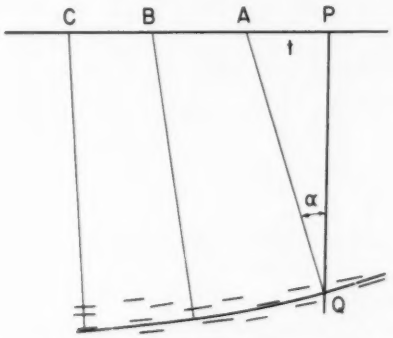


FIG. 10. Rice time section through limestone in well.

verted to normal velocities, $V_n$, by means of the $k$ factor (which has already been determined), and hence the normal distances, $N$, may be computed. The final limestone profile follows by a simple geometrical construction. The determination of the critical distance $2N \tan \theta_c$ with the aid of (5) for each value of $N$ should also be effected.

*The First Limestone Slice*

Table I gives the results of applying the above procedure to the measurements at Stolberg when the second event is regarded as a wide angle reflection ($WAR$). The $k$ factor is determined from the appropriate parameters in the first row where the distance, 1,100 ft S.W., corresponds to the ($vt$) of equation (12). If the event be regarded as a refraction, ($R$), $k$ has the unrealistic value of 1.01 and for this reason we infer that the second event is, in fact, a wide angle reflection.

In Figure 11 we show some of the normals, $N(WAR)$ of Table I and their associated velocities used in constructing the profile of the first limestone slice. It will be seen in the figure that the various normal velocities are increasing generally to the southwest and this is in agreement with the increasing proportion of older rock in the overburden in this direction, as determined by short range re-

TABLE I

Depth of first Rundle slice in well = $H$ = 11,020 ft
Vertical velocity to slice = 13,250 ft/sec
$V_2$ = 21,000 ft/sec
$k(WAR)$ = 1.08
$k(R)$ = 1.01

First Slice

| Distance from well | $T_{r_0}$ | $T_r$ | $X$ | $V_x(WAR)$ | $V_n$ | $N(WAR)$ | Critical Distance |
|---|---|---|---|---|---|---|---|
| 1,100 S.W. | 1.679 | 2.930 | 34,333 | 14,230 | 13,000 | 10,900 | 21,200 |
| 1,900 | 1.700 | 2.964 | 34,435 | 14,200 | 13,150 | 11,150 | 21,920 |
| 3,100 | 1.732 | 3.009 | 34,234 | 14,500 | 13,410 | 11,650 | 24,000 |
| 4,100 | 1.811 | 2.986 | 34,213 | 14,450 | 13,370 | 12,100 | 24,600 |
| 5,350 | 1.860 | 3.042 | 34,359 | 14,250 | 13,200 | 12,250 | 24,500 |
| 8,150 | 1.968 | 3.014 | 33,963 | 14,850 | 13,750 | 13,500 | 29,200 |
| 12,100 | 2.042 | 3.053 | 33,375 | 14,750 | 13,650 | 13,950 | 29,800 |
| 300 N.E. | 1.636 | 2.930 | 34,289 | 14,100 | 13,050 | 10,700 | 20,950 |
| 3,750 | 1.596 | 2.944 | 34,595 | 14,000 | 13,000 | 10,350 | 20,000 |

(Units are in ft and sec.)

fraction work. This work mapped an Upper Cretaceous seismic interface with a velocity contrast of 12,000/14,000 as illustrated, but this interface cannot be identified with a good geological marker although the thickening of the younger beds to the northeast of the well conforms to the geological section of Figure 9. To the southwest there is some apparent conflict between the two sections while, in addition, there is no seismic evidence for significant limestone faulting about 1½ miles from the well.

In Figure 12 the second event marked A refers to this first slice near the well. About a mile to the northeast of the well the event disappears and this is indicative of faulting, which is confirmed by the conventional reflection interpretation.

*The Second Limestone Slice*

The strong event marked B in Figure 12 is identified as emanating from the second slice and its greater amplitude is associated with a limestone thickness greater than that of the first slice. The thickness of the first slice is about 450 ft (or less than half a wave length) if we include 100 ft of a high velocity cherty limestone in the lower Jurassic, whereas the second slice (which may be combined with the third slice, as this same Jurassic member separates them) is at least 840 ft thick at the well.

The construction of the profile in this case is difficult as conventional reflections could not be identified with any certainty. Consequently values for $V_x$ were assumed to vary linearly from the value established from the known vertical velocity to the second slice and a value of $k$ of 1.08, to the $V_x$ determined from conventional reflections and second events farther to the northeast; while from these values of $V_x$, the normal depths were computed from the wide angle reflection formula.

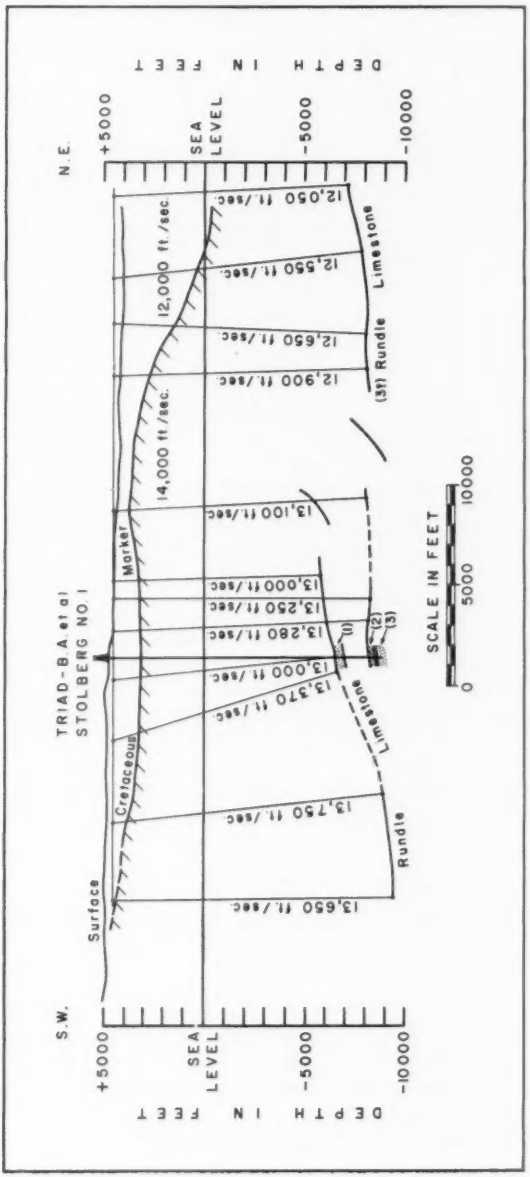


FIG. 11. Seismic profiles of limestone at Stolberg.

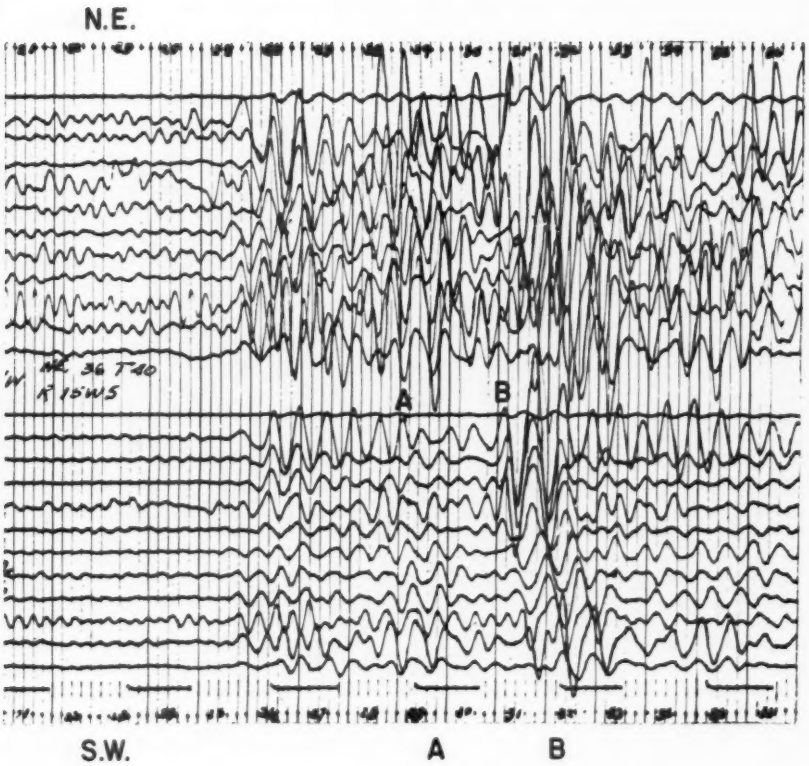


FIG. 12. Seismogram at Stolberg showing reflected events from first and second limestone sheets; broadside distance 34,470 to 34,710 ft; charge size 50 lbs; geophone 12 cps, amplifier gain 20 db, high cut off 40 cps.

Some evidence for faulting exists between the second slice and the third slice with which these northeasterly events are associated, as illustrated in Figure 11

*The Third Limestone Slice*

The second events from the third slice are shown very clearly at C in Figure, 13. Conventional reflection times were obtained by character correlation along continuous linear traverses to the known Rundle surface in a well some 18 miles to the northeast of Stolberg. This third slice is doubtless the autochthonous Rundle over which Inline Study No. 1 was carried out.

The decreasing normal velocities to this third slice in a northeasterly direction are indicated in Figure 11 and it is seen that they conform to the increasing thickness of younger formations with low velocity.

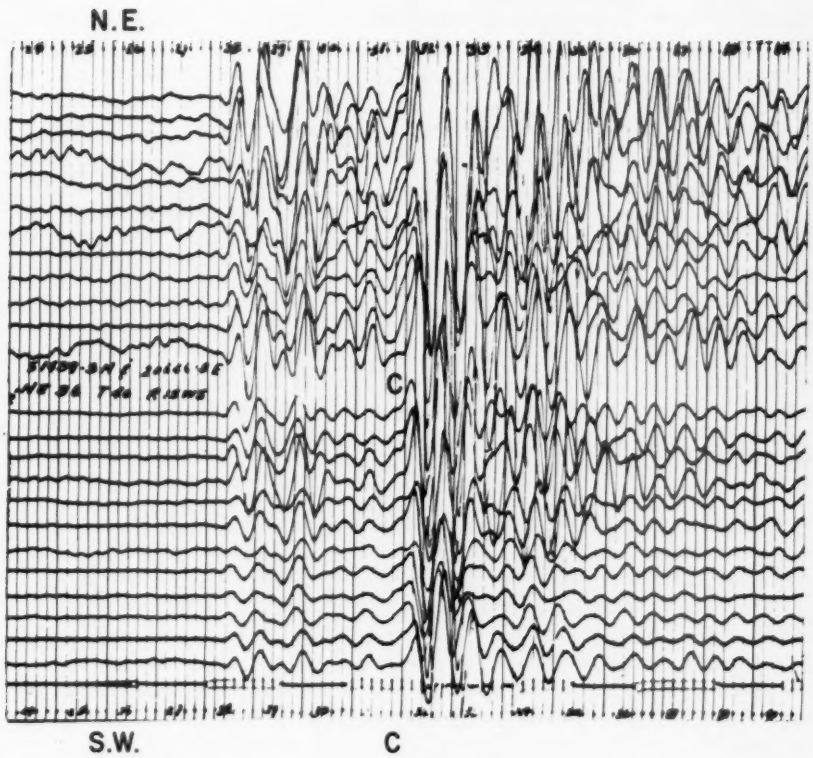


FIG. 13. Seismogram at Stolberg showing reflected events from autochthonous limestone; broadside distance 33,600 to 33,870 ft; charge size 150 lbs; geophone 12 cps, amplifier gain 20 db, high cut off 40 cps.

## GENERAL OBSERVATIONS

In converting bedding to normal velocities in the construction of Figure 11, it was assumed that anisotropy remained uniform throughout but, on studying Figure 9, it would appear that some variation could be expected, as the predominantly shaly part of the section, *KbK* is thought to be thickest near the well. The overlying beds, from *Kca* to *Ke* are estimated to contain about 50 percent each of shale and sandstone and they appear to thicken down flank so that the variation in the net overburden shale content may not be important. This is borne out by the fact that the adoption of uniform anisotropy leads to confirmation of the increasing or decreasing overburden velocity as suggested by the short range refraction observations.

The integration of the results of the two field procedures presupposes that

the normally reflected event from the effective limestone interface is identifiable, and this can only be the case when reflections are either continuously correlated or jump correlated on character grounds with the limestone reflections at a known well in the general area.

Second event inline observing along the direction of dip or across faults is inadvisable, for interpretation becomes involved. In this regard apparent reflection velocities may vary within wide limits, while the amplitudes of the events will be found to vary erratically on account of the varying stratigraphy and lithology in this direction.

Diffraction events may be expected from angular discontinuities and these have often been suspected from the geometry of the time-distance plot of the events and from their relatively low amplitudes.

In the interpretation of the second event in the past, especially at distances much beyond critical, refraction theory has rarely been satisfactory when applied to velocity "matching" of reverse shooting along inlines. On the other hand, in the wide angle reflection approach, interpretation will be found to be more consistent and computation much simpler.

## CONCLUSIONS

Wide angle second event reflection surveys are invaluable in the exploration of folded and faulted limestone structures.

Broadside shooting is probably the best known technique for locating important faults, while inline refraction shooting in strike directions provide necessary controlling information on limestone velocity and approximate depths.

In approximate strike directions and by an integration of the results of the second event and normal reflection methods, a good measure of the effective "bedding" velocity is achievable. From this the normal velocity, necessary in constructing profiles, is readily determined from the anisotropy factor of about 1.08, which appears to have wide application in the frontal structures of the foothills. This constitutes an important step forward in interpretation for in the independent application of the results from the two methods, normal velocities are assumed; and these assumed velocities could be seriously in error in cross-strike direction over dipping limestone structures.

The energy going into the refracted wave beyond the critical distance relative to the energy in the reflected wave is so small as to be undetectable in the geologically disturbed foothills belt. Indeed, it is most likely that this observation has a wider application such as in determinations of the crustal thickness of the earth. Late events that appear to be refracted from the Conrad or Mohorovicic discontinuities at distances near critical are most probably wide angle reflections. In this regard, however, the thickness estimates based on refraction theory and given by Richards and Walker (1959) would be modified by less than one percent, as the observation distances for both interfaces were not substantially greater than critical. In their crustal experiment, had the line been extended

so as to bring in the "Moho" as an identifiable first event refraction, it is almost certain that extremely heavy explosive charges would have been required as has been found to be the case wherever first event observations are made.

The theoretical predictions of large horizontal amplitudes in the reflected longitudinal events at second event distances are worthy of field investigation with a prospect of still further improving our interpretive technique in the resolution of folded and faulted geologic structure.

ACKNOWLEDGMENTS

The author is grateful to T. W. Morrison, J. R. Higson, W. Hryhor and M. M. de Leeuw of Triad Oil Company's geophysical department for assistance in computing, and to the Board of this Company for permission to publish this paper.

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GEOPHYSICS, VOL. XXV, NO. 2 (APRIL, 1960), PP. 408–432, 11 FIGS.

# AIRBORNE RADIOACTIVITY SURVEYS IN GEOLOGIC EXPLORATION*

R. M. MOXHAM†

## ABSTRACT

The value of airborne radioactivity surveys in guiding uranium exploration has been well established. Improved circuitry and development of semiquantitative analytical techniques now permit examination of more complex geologic problems. It is shown that the airborne technique can be used in exploration for thorium-bearing heavy mineral deposits and for uraniferous phosphorites.

The observed radiation intensity and configuration of the gamma radiation field may be used to approximate the equivalent uranium content and extent of the surficial part of such deposits. The equivalent uranium content of infinite sources can probably be determined within a few thousandths of a percent and the boundaries fixed within a few hundred feet. As the areal extent of the source decreases, the accuracy of the analytical results likewise decreases.

## INTRODUCTION

In the 1950's, many airborne radioactivity surveys for uranium were made by both private and government organizations and were quite successful in finding new uranium deposits, including some of the largest in the United States. The surveying problems involved were relatively simple and the attack straightforward, generally amounting to a search for relatively high-amplitude anomalies in geologically favorable areas. It is obvious, however, that the distribution of radioelements in earth materials involves many geologic processes in addition to the emplacement of uranium ore bodies. Recent improvements in circuitry and the development of semiquantitative analytical methods have advanced the surveying technique to a point where investigation of somewhat more complex geologic problems seems worthwhile.

Radioactivity associated with commercial mineral deposits is not confined to those valued for their uranium or thorium content. It is well known that placer deposits of titanium- and zirconium-bearing heavy minerals and marine phosphate deposits contain radioactive components in trace or by-product quantity. It is shown below that such deposits can thereby be detected from the air when they are sufficiently well exposed at the surface.

In addition to mineral exploration, the airborne radioactivity detector can provide data useful in correlating sedimentary geologic units. The detection system is sensitive to very small differences (about $\sim$10 ppm) in the equivalent uranium (eU) content of gross geologic features. It has been found that in many instances, the radioactive content of sedimentary rocks or of residual soils is directly related to their lithologic character. Variations in radioactive content that reflect such lithologic changes are within detectable limits, thereby permitting identification and lateral correlation of the lithology on the survey

* Manuscript received by the Editor July 7, 1959.

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records. This provides the geologist with a useful guide where outcrops are scarce or where the geology is poorly known.

A summary report describing some of the fields in which the airborne instrument can be useful has been recently presented at the United Nations Conference on Peaceful Uses of Atomic Energy at Geneva and has been published in the Proceedings of that conference (Moxham, 1958). Some important aspects of the application and interpretation of airborne surveys could not be discussed in the foregoing paper owing to space limitations. In some instances, supporting data had to be omitted for the same reason. The purpose of the present paper is to evaluate those aspects of airborne radioactivity surveying not heretofore discussed and to elaborate on some of the analytical problems sufficiently so that other members of the profession may more fully make use of the surveying instrument.

The discussion below deals solely with data obtained by the U. S. Geological Survey's airborne detector. However, the general analytical techniques employed and the conclusions drawn are in the main valid for any scintillation detector of comparable crystal volume and energy response.

The work described in this report was undertaken on behalf of the Division of Raw Materials, U. S. Atomic Energy Commission.

## SURVEYING

The radiation detection equipment used by the U. S. Geological Survey was designed by the Health Physics Division of the Oak Ridge National Laboratory. The circuitry is described in detail by Davis and others (1954) and Davis and Reinhardt (1957).

The detection element now used consists of 6 thallium-activated sodium iodide crystals four inches in diameter and two inches thick, connected in parallel. In some earlier surveys, only three crystals were used. The total pulse output from the crystals is fed through amplification stages and a pulse height discriminator (gated at 50 kev) to a count-rate recorder. Total radiation intensity is recorded by a graphic milliammeter. The sensitivity of the equipment when using six crystals is such that, in a radium gamma-ray flux of one microroentgen per hour, the count-rate is 225 per sec.

A simplified diagram of the equipment is shown in Figure 1.

The altitude of the aircraft is determined by a radar altimeter. Horizontal position is determined by an electromechanical marking system that keys the altimeter and radioactivity records to a 35 mm strip film exposed continuously along the flight path (Jensen and Balsley, 1946).

## GEOLOGIC DISTRIBUTION OF RADIOACTIVE MATERIALS

The geologic evaluation of airborne radioactivity data from systematic surveys is greatly enhanced by the use of the semiquantitative analytical technique devised by Sakakura (1957). Generally speaking, Sakakura's equations

are directly applicable only to certain simple geometric forms so that the complexities of nature must be synthesized from an appropriate combination of fundamental forms. The following discussion, therefore, will first describe surveys where the most simple geologic and geometric conditions exist, interpret them in terms of extent and grade of the source rocks, then treat the more complex situations by suitable synthesis. Needless to say, a preliminary study of all available geologic information is essential to any meaningful interpretation of flight data.

Adequate quantitative evaluation of surveys requires that parallel flight

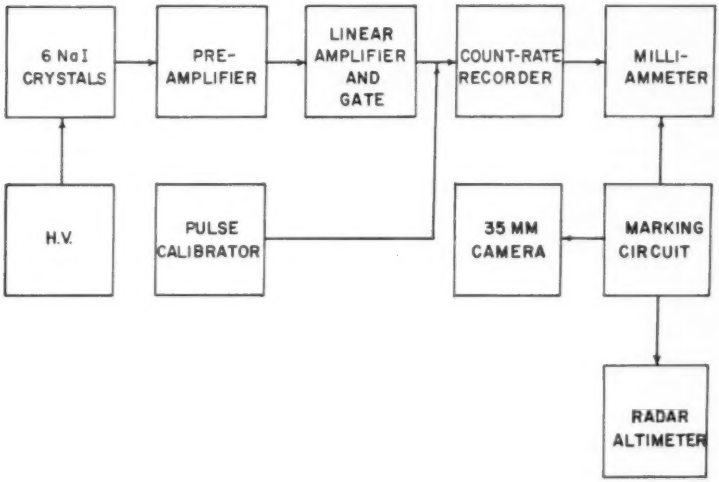



FIG. 1. Block diagram of Geological Survey airborne scintillation detector.

line configuration be employed. Linespacing will depend largely on the objective of the survey; but, in general, to resolve certain common radioactivity features, quarter-mile spacing is probably optimum. This is not to say that a region need be flown in its entirety at quarter-mile spacing. Preliminary flights might well be made on much wider spacing to determine qualitatively the response and distribution of gross radioactivity features. Additional closer-spaced coverage might be undertaken to obtain whatever quantitative data are required.

For instance, let us examine the central Coastal Plain area, Texas. In such an area, a survey might be desired for several reasons but discussion of two hypothetical objectives will suffice. We are concerned here with a province extending from the Edwards Plateau to the Gulf of Mexico, underlain by a gently southeastward dipping Tertiary and Quaternary sedimentary sequence. Uranium de-

posits of commercial importance occur in the Jackson group in the central part of the area.

Many of the lithologic units in the stratigraphic sequence are poorly exposed or obscured by residual soil. If a field geologist were interested in mapping a particular lithologic unit, an aerial radiometric survey at quarter-mile spacing in this area might provide very useful guidance as lithologic continuity is reflected on the radioactivity records under certain circumstances (see Moxham, 1958, Figure 2). On the other hand, the objective of the survey might be to evaluate the region for its uranium deposits. It has been shown that large (tens to hundreds of square miles) areas of abnormal radioactivity surround the most important near-surface deposits, so that a preliminary survey at perhaps five mile spacing might be made to find such anomalous areas. If the preliminary work were fortunate enough to delineate what appeared to be favorable areas, quarter-mile lines could then be flown to delineate the radiation details for quantitative evaluation.

For purposes of the following discussion on analytical techniques, quarter-mile flight linespacing and nominal velocity of 150 mph will be assumed.

*Distribution with infinite dimensions*

At an altitude of 500 ft above the surface, the minimum dimensions for an infinite source are approximately 1,200 ft in the direction parallel to the flight path, and 1,700 ft normal to flight direction (Sakakura, 1957, p. 36). The radiation curves over an infinite source are characterized by flattening at the peaks. Moreover, the lateral dimensions of the source assure that it will be detected on at least two adjacent lines. The average eU content of the source may be determined from the average net counting rate over the source (Sakakura, 1957, p. 10),

$$S = \frac{IS_0A_0}{2\pi C(1 - 0.342\mu x)e^{-\mu z}} . \qquad (1)$$

## *LIST OF SYMBOLS USED IN THIS PAPER*

$A$ = area of source
$A_0$ = areas of calibration source = 1,600 ft²*
$a$ = radius or width of source (feet)
$C$ = instrumental constant. For Geological Survey equipment
$C_1 = 3.19 \times 10^7$ (3 crystals)
$C_2 = 6.38 \times 10^7$ (6 crystals)
$H$ = area under curve recorded by counting-rate meter (counts)
$I$ = intensity recorded (counts-per-second)
$R$ = response of counting-rate meter
$RC$ = integrating time constant of count-rate circuit

$r$ = air distance between source and detector
$S$ = grade of source in percent equivalent uranium
$S_0$ = grade of calibration source = .35 percent equivalent uranium
$x$ = altitude of detector above source plane
$\theta$ = angle between flight path and a line normal to source center line
$\mu$ = linear absorption coefficient for the most penetrating gamma-ray of the $U$ spectrum = $1.46 \times 10^{-3}$ ft$^{-1}$ at sea level; $1.25 \times 10^{-3}$ ft$^{-1}$ at 5,000 ft altitude

* Calibration source used by the U. S. Geological Survey is located at Walker Airport, Grand Junction, Colo.

It is also desirable to determine the geographic location of the contact between two infinite geologic units. Theory dictates that the contact is at the half maximum. However, in practice there will be a horizontal displacement (lag) of the geographic position of the half maximum owing to the finite response time of the instrument. Lag has been previously discussed in some detail (Moxham, 1958, p. 2). It seems sufficient to state here only that lag, as determined experimentally, amounts to about the distance traveled in one time constant for infinite sources; it is considerably less for point sources.

From the foregoing statements it would seem that the radioactivity data from a systematic airborne survey could be used in a straightforward manner to locate contacts between geologic units having infinite dimensions if lag is removed from the data. Further consideration, however, brings out certain difficulties. The geologic contact in the subsurface may indeed be a relatively sharp interface, but more often than not, the boundary at the surface is obscured by soil development and weathering. The attendant processes result in surficial redistribution of the radioactive materials that often obscures the boundary or gives rise to a quasi-transitional boundary. Moreover, it is usually necessary that the most up-to-date base maps be utilized in flight operations and compilation of the data. It seems preordained that the available geologic maps are compiled on older, and in many instances, less accurate base maps. A principal source of discrepancy between the contact location based on the flight data and that mapped by the geologist often results from differences in the base maps used by the respective workers.

We have spoken thus far in rather general terms. Examination of the results of some specific surveys may be more enlightening both in regard to the behavior of certain types of radioactive deposits and to their quantitative evaluation.

*Phosphate deposits.*—Marine phosphate deposits commonly contain uranium in the range 0.00× percent and although commercial-size deposits in the United States are presently valued mainly for the content of $P_2O_5$, uranium is being recovered as a byproduct from land-pebble deposits in Florida. Land-pebble deposits are those containing phosphorite pebbles in the poorly consolidated Miocene formations, mainly in the central part of the Florida peninsula.

In 1953, extensive airborne surveys were made in geologically favorable areas in the southeastern states (Moxham, 1954; Meuschke, 1955) to locate uranium-bearing phosphate. The following discussion concerns only the surveys over phosphate terrane in Florida, but the results are applicable to exploration for uraniferous phosphorites in general.

A survey was made in Marion County, Florida (Moxham, 1954), a few miles south of Ocala, where outliers of the Hawthorn formation (Miocene) rest upon

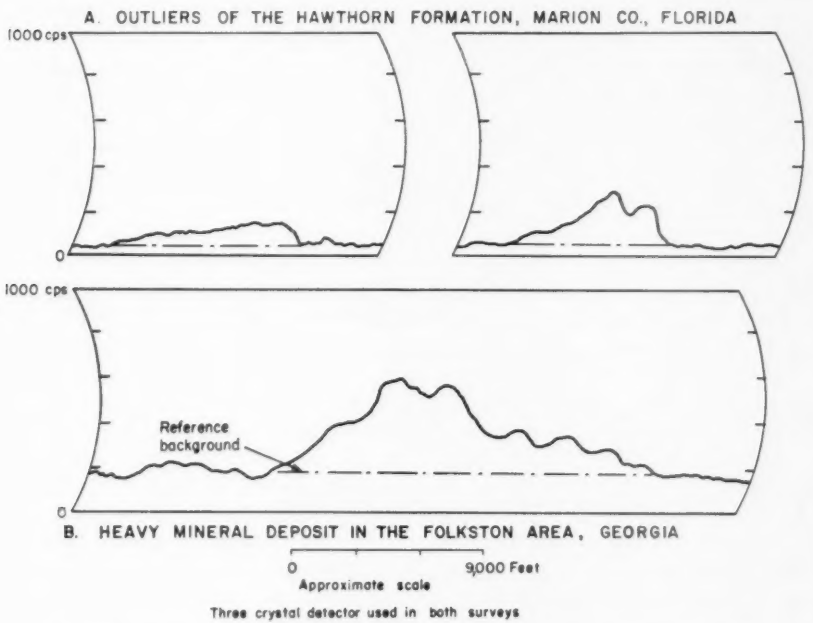



FIG. 2. Examples of airborne radioactivity profiles at 500-ft altitude over infinite sources.

the Ocala limestone (Eocene). The Hawthorn outliers consist of clay and sand containing uraniferous phosphorites and phosphate pellets. The area of Ocala limestone surrounding the outliers is mantled by a thin layer of soil or sand (Espenshade, 1958).

Typical radioactivity profiles are shown in Figure 2A. In most localities the profiles show flattened anomalies. Where peaks occur, they tend to be rounded. Moreover, as the abnormal radioactivity commonly extends from about one to 6 miles along the profiles and has lateral continuity on the same order (Figure 3), the principal anomalous areas no doubt represent infinite sources. There also appear to be transitional rather than sharp geologic boundaries. The limits of

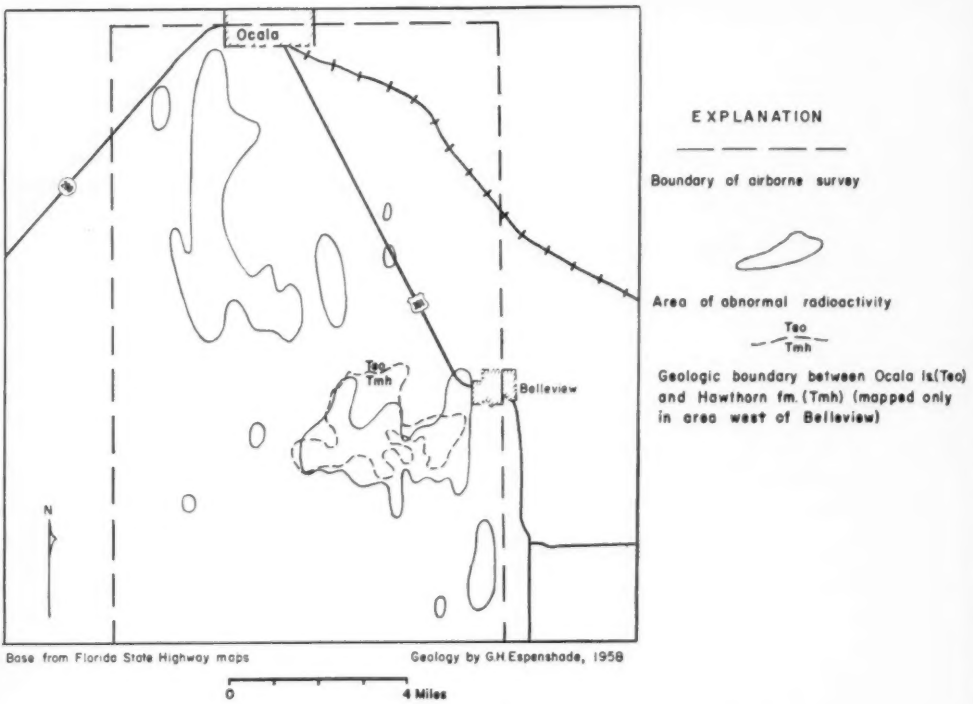



FIG. 3. Airborne radioactivity survey of part of Marion County, Florida.

the anomalies shown in Figure 3, in the absence of clear cut half-maximum values, were arbitrarily assumed to enclose those radiation intensities exceeding the reference background level (see Figure 2A) recorded over the soil and sand surrounding the Hawthorn outliers.

G. H. Espenshade found that the anomalous areas are underlain by three types of radioactive materials: loose quartz sand containing about 0.001 percent eU; clay, locally phosphatic, containing from 0.002 to 0.006 percent eU; and leached porous phosphatic sandstone averaging about 0.018 percent eU. The average net peak intensities recorded over the anomalous areas ranged from about one hundred to four hundred cps which, from equation (1), indicates the average eU content ranges between .001 and .003 percent. It would be inferred, therefore, that the areal extent of the phosphatic clay predominates over the higher grade phosphatic sandstone. Although no quantitative measurements were made on the ground, the foregoing conclusion is generally substantiated by field observations.

In one anomalous area, southwest of Belleview (Figure 3), eight samples of leached phosphorite averaged .018 percent eU and 14.0 percent $P_2O_5$. Pellet phosphorite beds were cut in auger holes at two localities. The beds range from several ft to $14\frac{1}{2}$ ft in thickness. Total $P_2O_5$ ranges from 3.1 to 20.8 percent.

The geologic boundary between the Hawthorn and Ocala formations has been mapped in the area southwest of Belleview. Comparison of the mapped boundary with that inferred from the airborne survey shows that the location and general dimensions of the outlier are reasonably close, but there is little agreement in detail, as one would expect under the circumstances.

*Heavy mineral deposits.*—Heavy mineral deposits containing titanium- and zirconium-bearing material are of economic interest and can be detected from the air under proper circumstances. Deposits of this type in the Coastal Plain of the southeastern states are associated with shorelines developed during Pleistocene time (MacNeil, 1949).

One of the most important heavy mineral deposits in the United States is associated with old beaches on Trail Ridge, a remanent of a barrier island, in north-central Florida. Layers range in heavy mineral content from less than one percent to local concentrations greater than six percent. The deposits probably average about four percent heavy minerals. Rutile and ilmenite are the minerals of greatest economic importance. Mineral grain analyses (Thoenen and Warne, 1949, p. 35) show that the major non-opaque heavy-mineral constituents include at least two that can be expected to be radioactive, zircon and monazite.

The potential detectability of such deposits by airborne methods depends upon the vertical distribution of the heavy minerals. At Trail Ridge and generally elsewhere in the southeast, the maximum concentration of heavy minerals is ordinarily at depths ranging from 10 to 60 ft. However, in nearly every instance, some of the layers of heavy minerals extend to the surface. Whether or not the deposits can be detected from the air depends on the concentration and surface extent of such layers. At Trail Ridge there are apparently insufficient heavy minerals at the surface as abnormal radioactivity was not detected on three flights crossing the deposit at different localities.

More successful results were obtained over heavy-mineral deposits in the vicinity of Folkston, Georgia (Moxham, 1955) where six areas of abnormal radioactivity were delineated. A typical radioactivity profile from the Folkston survey (Figure 2B) demonstrates that the concentration and surficial distribution of the heavy minerals are sufficient at this location to permit detection easily. The anomaly on the profile in Figure 2B represents an increase of about 350 cps above the reference background which from equation (1) indicates an increase in eU content of about 0.003 percent.

No information is available on the actual distribution of the heavy minerals at Folkston. It is inferred from the airborne records that the limits of deposition are rather diffuse at the surface and sharp boundary conditions do not exist.

It is concluded on the basis of the foregoing surveys and those previously

described (Moxham, 1958) that the eU content of infinite sources probably can be determined within a few thousandths of a percent. The delineation of source boundaries is dependent on the nature of the contact. A sharp, well-exposed geologic boundary between strongly contrasting sources can be located within perhaps 300–600 ft but accuracy decreases to very generalized delineation as geologic conditions depart from this ideal situation.

*Distribution with less-than-infinite dimensions*

The term, finite, which seems more appropriate to use here, has been restricted by Sakakura (1957, p. 21) to a particular geometric configuration. To avoid confusion his terminology will be retained in this report.

The dimensions of infinite sources are sufficiently large to be easily recognized on the radiation profiles. As previously stated, the curves show some evidence of flattening at the peak, a feature that usually distinguishes them from curves arising from less-than-infinite sources. As the source dimensions decrease from infinite to less-than-infinite proportions, the source geometry becomes increasingly difficult to analyze. The most satisfactory analysis will probably require quarter-mile spaced, parallel flight lines. It is then possible to utilize the Sakakura (1957, p. 33) analytical technique, briefly summarized below (500 ft flight altitude is assumed).

If an anomaly is detected on only one flight line, a point source is indicated. If radiation from a source is detected on two lines, three source configurations are possible; slab, line, or finite. Should the peak intensity ($I$) and area under the curve ($H$) on each line be approximately the same, a slab or line source is indicated. The width of the source may then be determined by the ratio $H/I$. If the anomalies show markedly dissimilar values of $H$ and $I$ on adjacent flight lines, a finite source is indicated. Sakakura's work has shown that the dimensions of the fundamental geometric configurations are as follows:

*Slab source:* rectangular, length >1,700 ft, width <1,200 and >800 ft.
*Line source:* rectangular, length >1,700 ft, width <800 ft.
*Finite source:* circular, radius <850 ft and >275 ft.
*Point source:* circular, radius <275 ft.

Although the geometries defined above seem to set forth rather rigorous conditions, it is shown below that an erroneous analysis of geometric configuration per se will not lead to gross errors in computations of grade. Instead, the magnitude of the error is more closely related to the estimation of the total surface area of the source. For instance, if a large slab source is mistakenly treated as an infinite source, the errors in position of the boundaries and eU content will not be excessive. If, on the other hand, an infinite source anomaly is erroneously treated as a point source, order of magnitude errors may be expected.

*Phosphate mine (slab source).*—As an example of a source that is on the borderline between less-than-finite and infinite dimensions, consider an open-pit phosphate mine in Polk County, Florida. Here, discarded leached phosphate con-

taining a relatively small amount of uranium occurs in a well-defined rectangular configuration. The uraniferous source is surrounded by very weakly radioactive Pleistocene terrace sands.

A plan view of the phosphate mine is shown in Figure 4. The dimensions of the mine at the time of the survey, 2,800 by 1,150 ft, are such that it constitutes a slab source, but nearly at the upper finite limit. Flights over the mine were made in an eastward direction along the lines shown, parallel to the long axis. Figure 4 shows the net peak intensity ($I$) to be about 1,600 cps. If an infinite source configuration and a value of 1,600 cps for $I$ are assumed, use of equation (1) indicates the material in the pit has an average eU content of 0.012 percent. The average eU content of twenty-five composite samples of the uraniferous leached phosphate was 0.011 percent eU. From these results we conclude that for large, less-than-infinite sources, it makes little difference if the dimensions are overestimated and the grade calculation made with the infinite source equation. As a matter of fact, the infinite source solution was more accurate than the slab source solution as shown below.

The contoured radiation data were used to determine the theoretical source boundary. From considerations given above, the boundary should coincide with the half-maximum (975 cps) contour midway between the reference background (350 cps) and the average peak intensity (1,600 cps). The 975 cps contour roughly outlines the known boundary of the mine except that there is an apparent displacement of about 300 ft eastward, probably due to recording lag which was not removed in compilation of these data.

To obtain data for a slab-source analysis, five flights were later made with the six crystal detector along each of three lines oriented at approximate angles of 0°, 44°, and 62° to the long axis of the deposit. The averaged data are given below:

| $\theta$ | $H$ | $I$ | $H(\cos\theta)/I$ |
|---|---|---|---|
| 0° | $11.8\times10^3$ | $2.23\times10^3$ | 5.3 |
| 44° | $15.6\times10^3$ | $1.69\times10^3$ | 6.6 |
| 62° | $32.9\times10^3$ | $3.11\times10^3$ | 5.0 |

The $H\cos\theta/I$ ratio is a function of the width of the slab as shown in Figure 5. Source widths of 750, 1,200, and 630 ft are indicated by the flight data tabulated above. The actual width of the phosphate pit is 1,150 ft.

If slab source configuration is assumed, equation (2) (Sakakura, 1957, p. 42) is applicable:

$$S = \frac{IS_0A_0}{2C_2G_1}. \qquad (2)$$

Numerical solution of the function $G_1$, which relates the instantaneous radiation intensity to the width of the slab and spatial position of the detector, has been tabulated by Sakakura (1957). Using the observed source width (1,150 ft) and

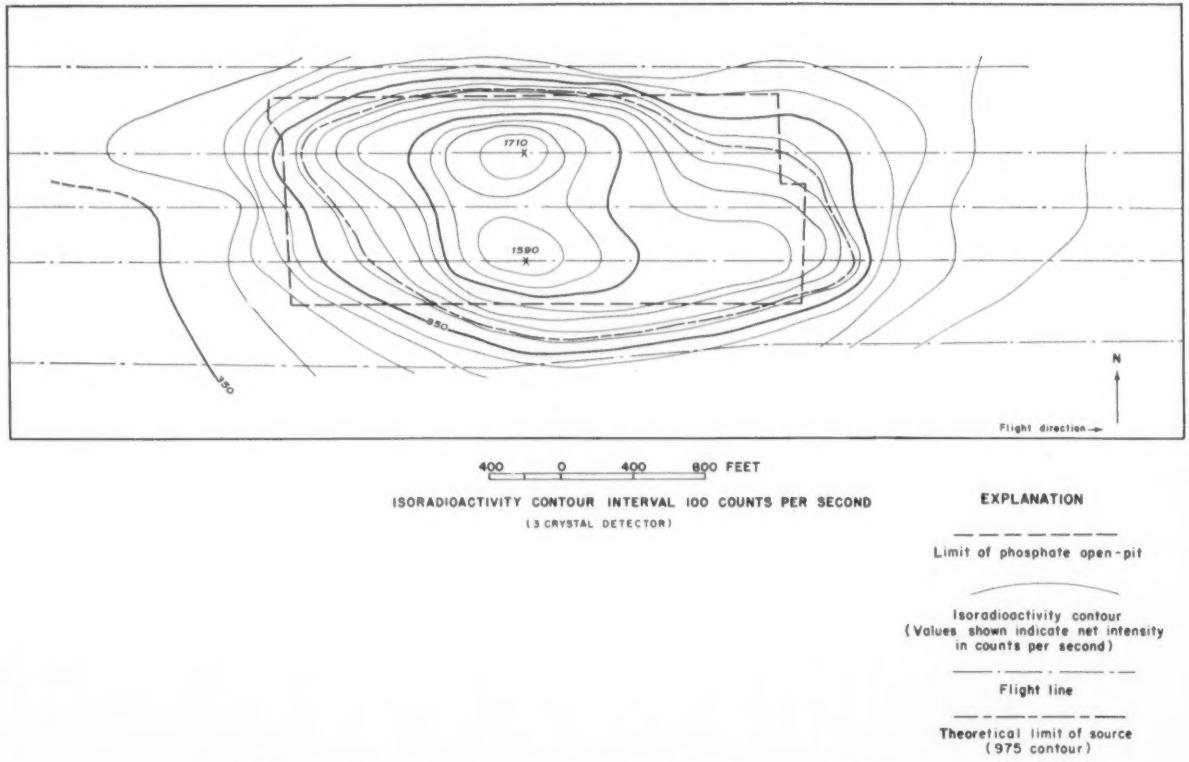



FIG. 4. Map of an open-pit phosphate mine showing isoradioactivity contours at 500-foot altitude.

the flight data tabulated above, solution of equation (2) gives eU values of 0.010, 0.006, and 0.016 percent respectively, for angles of 0°, 44°, and 62°. If the computed source widths are used to compute grade, the results are .007, .004, and .012 percent eU, respectively. The actual eU content of the source as previously stated is 0.011 percent.

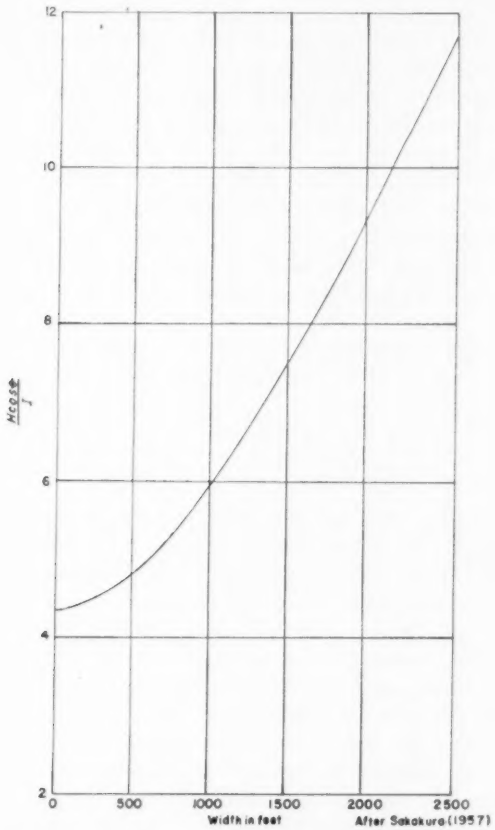



FIG. 5. Relationship of $H \cos \theta / I$ to width of slab sources.

*Beach placer deposit (line source).*—Analysis of flight data made over a beach placer deposit has been briefly described (Moxham, 1958). It was not possible in the foregoing report to give supporting data or to describe adequately the methods used. We will endeavor to do so below.

An airborne radioactivity survey was made in 1953 along the Atlantic coastline (Moxham and Johnson, 1953; Meuschke and others, 1953) to determine the

response of the radiation detector to modern beach placer deposits of heavy minerals. Deposits were known to occur at many localities, but it was not known whether they contained sufficient radioactive minerals or were sufficiently large and well exposed to permit detection from the air.

Nineteen localities of abnormal radioactivity were detected. A cursory consideration of the geologic setting indicates that the modern beach placers would be oriented generally parallel to the coastline and that their configuration would approximate a slab or line source, depending upon the width of the mineral concentration. At one locality on Anastasia Island, Florida (Figure 6), flight lines oriented at three different angles were made over an anomalous area. The resulting anomalies were quite asymmetrical, apparently because the beach deposit was adjoined on the east by inert seawater, on the west by a few hundred ft (width) of slightly radioactive dune sand, and still farther landward by very inactive sand. In order to eliminate these extraneous effects it was necessary to reconstruct the anomalies by using the radiation intensity over the water as the reference background and modifying the landward part of the curve so as to be symmetrical with the seaward part, as, for all practical purposes, the source lies at the land-sea boundary.

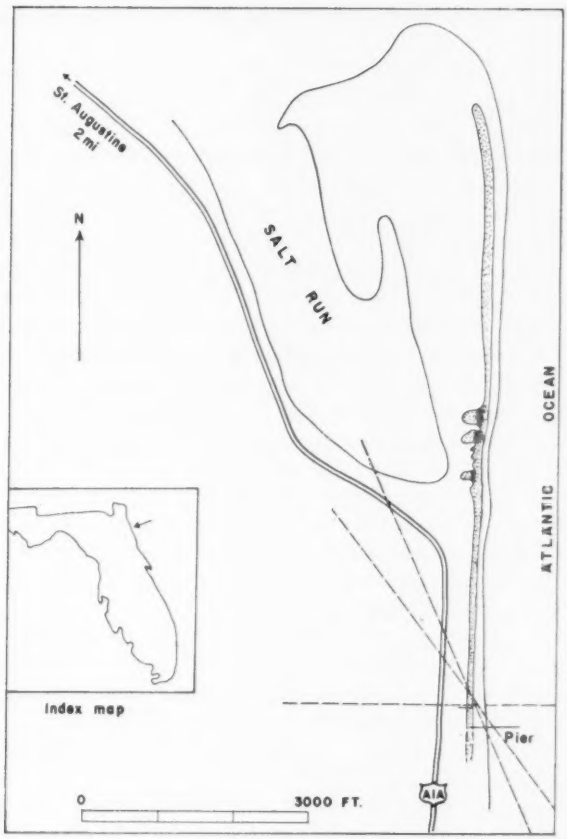
Five passes were made along each of the three flight lines. The average data obtained from the reconstructed curves are summarized as follows:

| $\theta$ | $H$ | $I$ | $H(\cos\theta)/I$ |
|---|---|---|---|
| 0° | $2.15\times10^3$ | $4.8\times10^2$ | 4.5 |
| 53° | $4.44\times10^3$ | $5.7\times10^2$ | 4.7 |
| 66° | $5.58\times10^3$ | $6.0\times10^2$ | 3.8 |

At $\theta=66°$, the $H(\cos\theta)/I$ ratio of 3.8 is impossibly low because the smallest value theoretically attainable is 4.3 as indicated on Figure 5. The values of $H(\cos\theta)/I$ for 0° and 53° indicate the width of the placer deposit to be 250 and 470 ft respectively. Ground radioactivity surveys at Anastasia Island indicate the width of the radioactive zone to range from 20 to 300 ft, averaging perhaps 150 ft, so that the computed values are high, probably by a factor of two to five. However, it is important to note the manner in which the $H(\cos\theta)/I$ ratio changes with source width. The curve of this function is quite steep for widths 500 ft and greater, so that a relatively small variation in source width is detectable. However, for widths less than 500 ft the slope of the curve decreases markedly so that variations in source width effects only slightly the $(H\cos\theta)/I$ ratio. From a practical standpoint, $H(\cos\theta)/I$ probably cannot be determined closer than $\pm$ ten percent. Such errors mean that the width of a line source is exceedingly difficult to determine on the basis of the airborne measurements alone. This statement applies to a surveying altitude of 500 ft and may not hold true at substantially lower altitudes.

As the $H\cos\theta/I$ values tabulated above indicate a line source, equation (3) is required for determination of grade:

$$I = \frac{2CS}{S_0A_0}\mu^2 ax\left[\frac{K_{1(\mu\omega)}}{\mu\omega} - .342\,K_{0(\mu\omega)}\right], \qquad (3)$$




EXPLANATION

DEPOSIT OF RADIOACTIVE HEAVY MINERALS (DENSITY OF STIPPLE PATTERN INDICATES RELATIVE RADIATION INTENSITY ON THE GROUND)

FLIGHT LINE

FIG. 6. Sketch map showing beach placer deposits, Anastasia Island, Florida.

where $\omega^2 = x^2 + y^2$ and $K_1$ and $K_0$ are Bessel functions of the second order kind (Watson, 1952).

The symbol "$y$" designates the horizontal distance from the center of the source to the vertical projection of the point of observation. Here, we will use values observed where $y = 0$. Solution of equation (3) for the tabulated data gives an eU content of 0.004 percent for the flights at $0 = 53°$ and 0.007 percent for the flights at $0 = 0°$.

Twelve samples of the beach placer deposit collected in the area scanned by the flight lines average 0.012 percent eU, resulting chiefly from zircon and monazite. The average computed grade is low by a factor of about two.

*Uranium deposits.*—One of the primary uses of the airborne radioactivity detector has been, and no doubt will continue to be, to facilitate uranium exploration. Airborne surveys were chiefly responsible for finding uranium deposits that lead to development of several of our most productive areas. The Delta mine on the San Rafael Swell, the Jackpile mine in the Grants-Laguna area, and mines in the Washaki Basin (Maybell area, Colo.) are among the more notable. Uranium in the Coastal Plain area of Texas was also first found by an airborne detector, although the primary survey objective was to locate oil structures.

Surveys by the Geological Survey have been made mainly in the Colorado Plateau, central Plains, and Coastal Plain areas, and have dealt principally with deposits of oxidized uranium minerals in sedimentary rocks so that the following discussion deals exclusively with such deposits.

Outcrops of uranium ore proper (as distinguished from the ore plus its aura) are generally of less-than-infinite dimensions. However, it is known that the reference background may be abnormally high in regions where uranium minerals occur (Moxham, 1958; Moxham and others, 1957). Examples of the data recorded in two different areas of uranium deposits in sedimentary rocks are given below.

*Finite source.*—Deposits of oxidized uranium minerals in the Browns Park formation of Miocene (?) age were detected during an airborne survey of the Washaki Basin, Carbon County, Wyoming, and Moffat County, Colorado, in 1953 (Henderson, 1954; Johnson, 1955). An analysis has been made of the flight data from sec. 5, T. 12 N., R. 92 W. in the Poison Basin area where detailed geologic data are available (Vine and Prichard, 1954). The radiation intensity profiles of parts of lines 11 and 12 are shown in Figure 7. The positions of the flight lines and peak intensities, located as accurately as possible from aerial photos, are shown in Figure 8. Inspection of lines 10 and 13 showed no abnormal radioactivity in this area, so we have a situation where anomalies of unequal amplitude are present on two adjacent flight lines spaced at a quarter-mile interval. A finite source situation is therefore suggested. There are apparently three sources denoted by peaks $A$, $B$, and $C$. The curve containing peaks $A$ and $B$ appears to represent two anomalies that have not been fully resolved. It should be noted that the easternmost anomaly (peak $C$) is beyond the area of

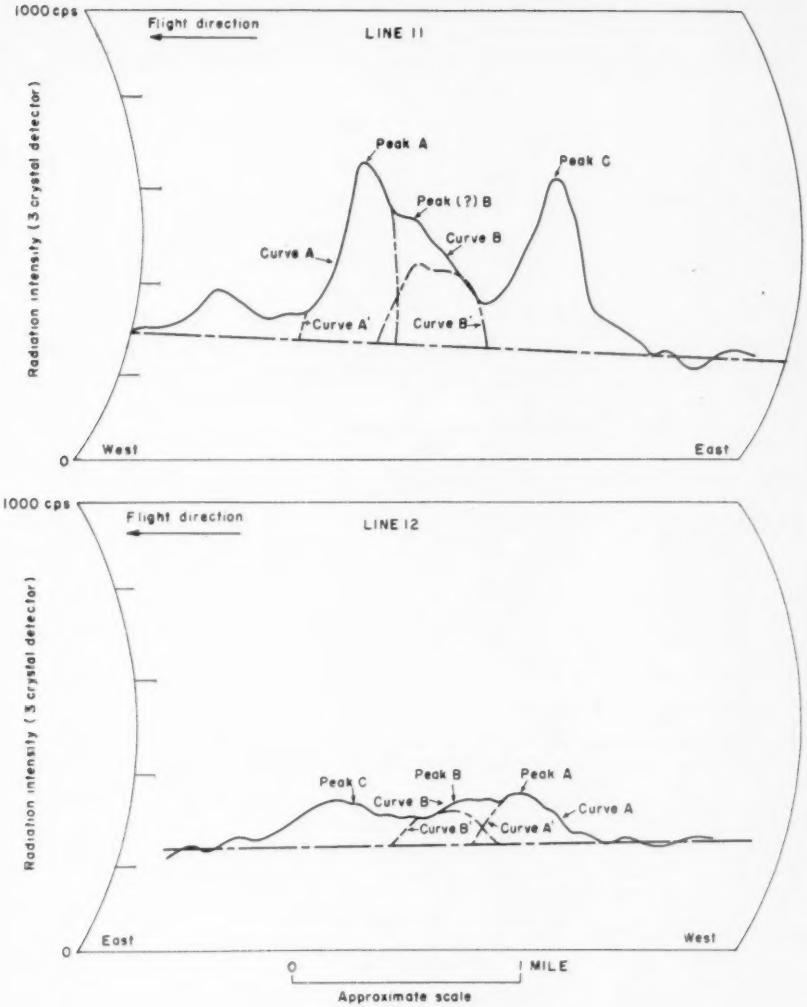
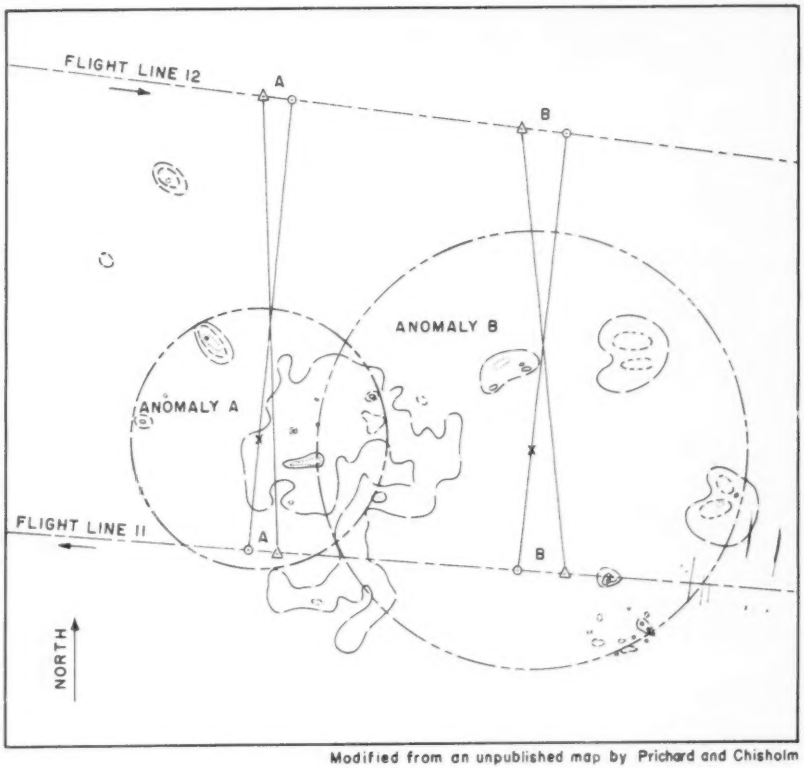



FIG. 7. Radioactivity profiles at 500-ft altitude along lines 11 and 12, Poison Basin area, Wyoming.




Modified from an unpublished map by Prichard and Chisholm

250 0 250 500 750 1000 FEET

Approximate scale

EXPLANATION

Flight line

○ Theoretical △ Observed
Location of anomaly peak

Computed source boundary

0.03
0.06
0.12
0.24

Ground isoradioactivity contours
(milliroentgens per hour)

FIG. 8. Ground radioactivity survey of part of the Poison Basin area Carbon and Sweetwater Counties, Wyoming.

the investigation, but has been shown in Figure 7 as it partially overlaps *B*. The discussion below will deal only with *A* and *B*.

If the anomaly containing peaks *A* and *B* is assumed to be an overlap of two curves, *A* and *B;* the component curves must be resolved in order to analyze the source geometry and grade. First, curve *A* was reconstructed so as to be symmetrical. The curves were then subtracted by successive approximation to arrive at the resolved curves *A'* and *B'*.

We have assumed then, that there are two sources: source *A*, represented by the *A'* curves, and source *B*, represented by the *B'* curves. These sources lie somewhere between lines 11 and 12, and we can further assume that the centers of the two anomalies lie on the lines connecting the theoretical peak locations (Figure 8). Owing to the relative amplitudes, the centers of the sources are closer to line 11 than line 12.

The data from the reconstructed curves are summarized below:

| Line No. | Curve | *H* | *I* | *H/I* |
|---|---|---|---|---|
| 11 | *A'* | 2,150 | 390 | 5.5 |
| 11 | *B'* | 1,390 | 180 | 7.7 |
| 12 | *A'* | 710 | 115 | 6.2 |
| 12 | *B'* | 450 | 75 | 6.0 |

The radius of a finite source and the distance from the center of the source to the nearer of the two flight lines is a function of the relationship between *H/I* ratios as shown in Figure 9. The *H/I* ratios indicated above yield a radius of 530 ft for source *A*. The ratio for source *B* does not fall within the graph, which immediately indicates that all is not well. We are forced to assume that the radius is large and will accept the nearest point on the graph, i.e., 900 ft. The distance from the centers of sources *A* and *B* to the nearest flight line (11) are about 460 and 500 ft respectively.

The grade-area product (*SA*) of the two sources may be calculated from the point source equation (4) and by means of an appropriate factor (table 1) can be converted to finite form:

$$SA = \left[\frac{S_0 A_0\ 500\pi}{2C\mu}\right]\left[\frac{H}{4.36\ I^{0.788}}\right]^{4.72}. \qquad (4)$$

TABLE 1. CONVERSION FACTORS TO CORRECT POINT SOURCE GRADE-AREA TO FINITE SOURCE GRADE-AREA

| Radius (a) (ft) | Minimum | Average | Maximum |
|---|---|---|---|
| 0 | 1.000 | 1.000 | 1.000 |
| 400 | .714 | .765 | .813 |
| 500 | .568 | .613 | .684 |
| 600 | .426 | .477 | .540 |
| 700 | .324 | .368 | .425 |
| 800 | .244 | .276 | .319 |
| 900 | .185 | .207 | .233 |
| 1,000 | .139 | .151 | .167 |

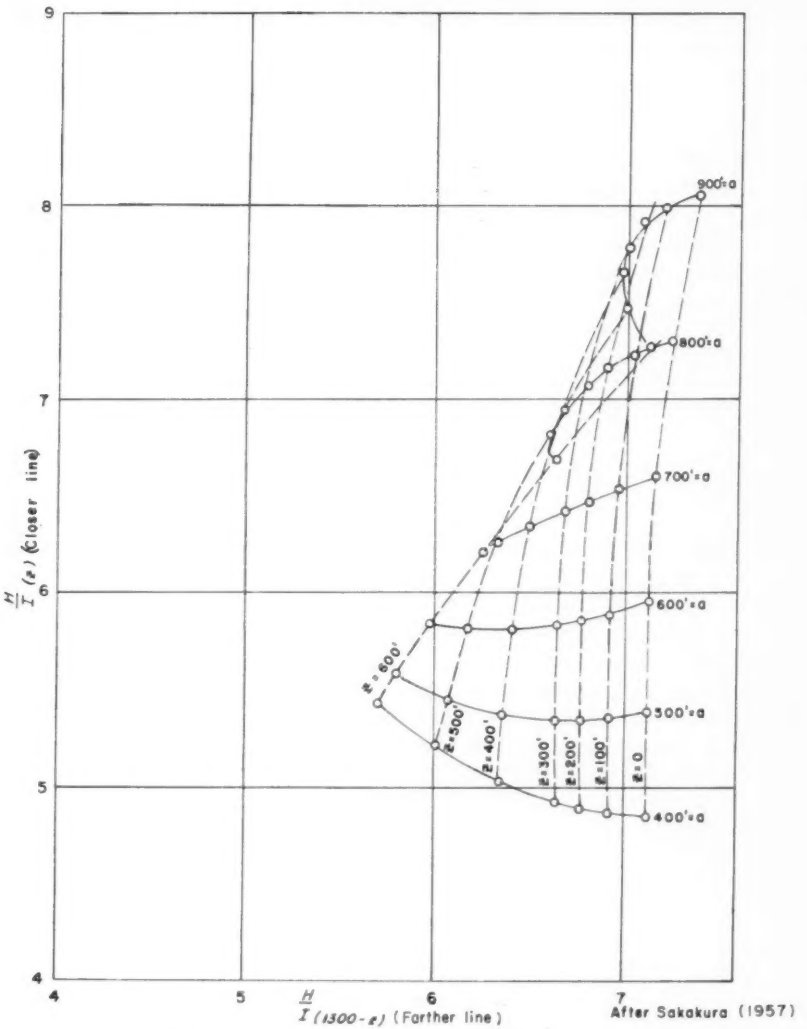



FIG. 9. Relationship of $H/I_{(a)}$, $H/I_{(1200-a)}$ and radii (a) of finite sources.

Solution of equation (4) using the data from the reconstructed curves and application of the appropriate conversion factors indicate that the eU content of sources *A* and *B* is 0.006 and 0.001 percent, respectively.

The computed source boundaries have been plotted in Figure 8. Instead of

two sources as the flight records would indicate, there are in reality several local concentrations of radioactive material. In anomaly *A*, the local concentrations are scattered over an area that on the whole is abnormally radioactive. The computed center of anomaly *A* is offset perhaps 200 ft to the west, which is probably a combination of lag and errors in transferring the airborne data from photos to the base map. However, the computed size of anomaly *A* is reasonable. Anomaly *B* partly overlaps anomaly *A*, as the unresolved radiation profile curves would suggest. In area *B*, the concentrations of radioactive material are more widely scattered. The computed radius embraces an area that is obviously too large.

In regard to the observed grade of the anomalies, the ground radioactivity surveys (Figure 8) indicates the average radiation intensity in area *A* is about 0.03 mr/hr which in turn indicates the eU content of the rocks is essentially in agreement with the value computed from the airborne data. In area *B*, the radioactivity is so dispersed that we can only estimate that the eU content is considerably less than that in area *A*. As the computed area of *B* is too large, we can expect the computed eU value, 0.001 percent, to be too low. The average reference background in area *B* from the airborne data is about 270 cps which indicates that host rocks contain about 0.001 percent eU. The recorded anomaly necessarily represents an increase above the background, but the computed value does not reflect that.

*Point source.*—A review of the Geological Survey flight records to obtain typical examples of point source anomalies showed that such sources were indeed rare. Even in areas where the uranium minerals are highly localized for the most part, such as in the Pumpkin Buttes area of the Powder River Basin, northeastern Wyoming, an anomaly is seldom confined to a single flight line, as would be dictated if true point source conditions prevailed. The two examples given below that did meet point source specifications were exceptions rather than the rule.

The Pumpkin Buttes area is underlain by sandstone, shale, and coal of the Fort Union (Paleocene) and Wasatch (Eocene) formations. Deposits of secondary uranium minerals are found in "rolls" and disseminated in several sandstone layers in the Wasatch formation. The grade and area of the materials involved range from slightly abnormal "soil highs," extending for several hundreds of square ft, at which no uranium minerals are apparent at the surface, to small highly mineralized pods usually amounting to a few tons or less of ore containing uranium in the 0X.0 percent range. The surface area of such deposits seldom exceeds a few tens of square ft.

The airborne survey of the Pumpkin Buttes area, which resulted in the discovery of radioactive deposits in this region, covered approximately 830 square miles in Johnson and Campbell Counties. Flight lines were oriented east-west, spaced at quarter-mile intervals, and flown at a nominal 500-ft altitude. The locations of anomalous radioactivity detected from the air are shown in a report

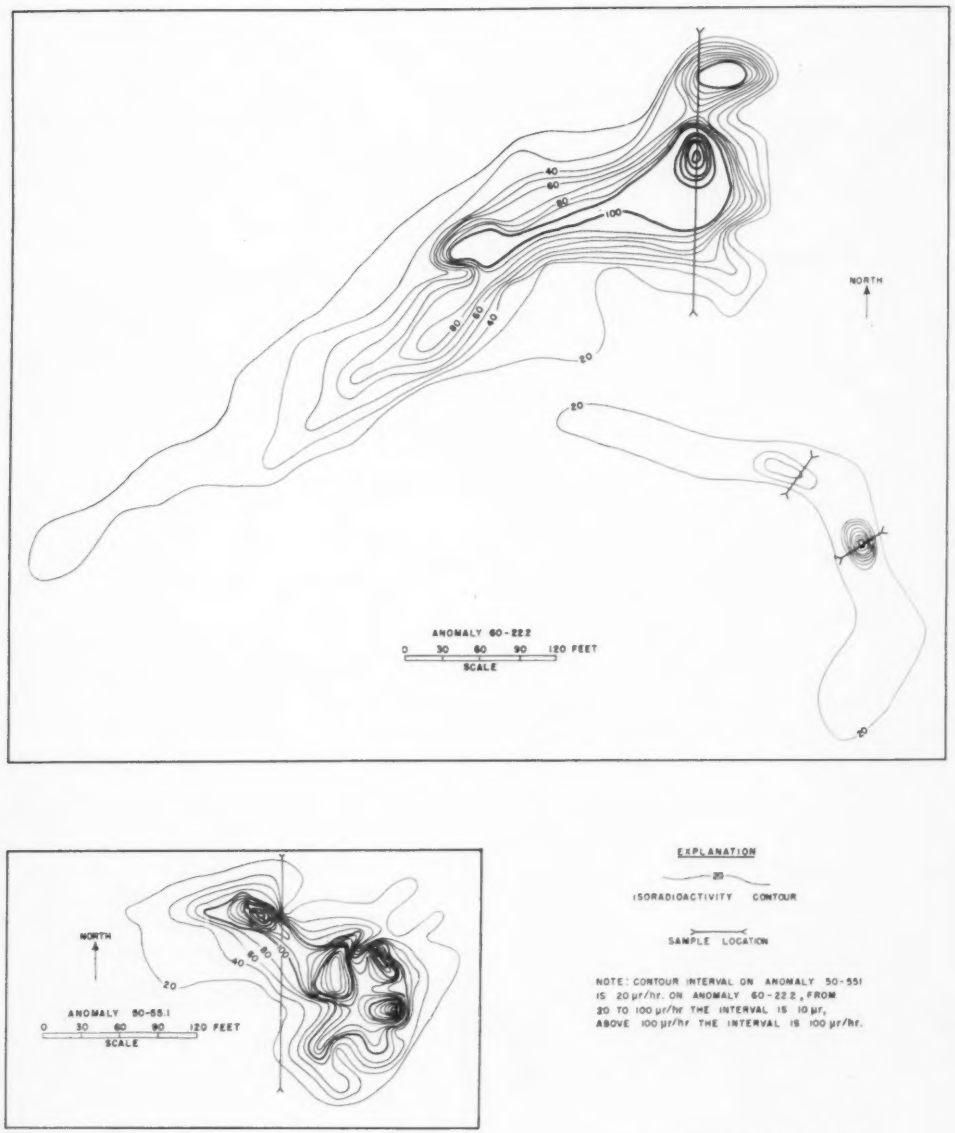



FIG. 10. Isoradioactivity contour maps of point source anomalies, Powder River Basin, Wyoming.

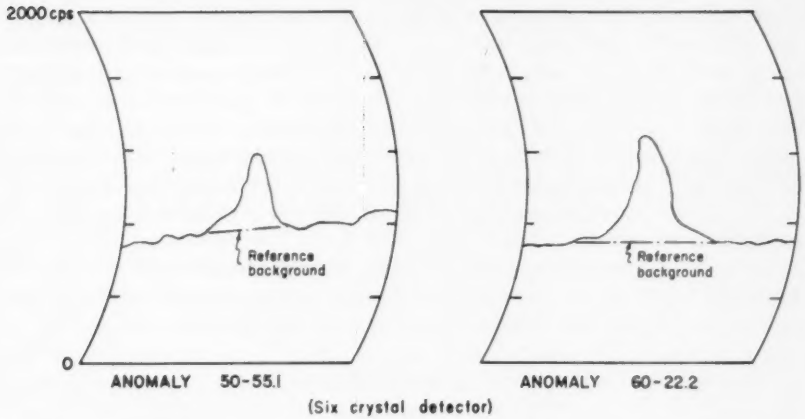



FIG. 11. Radioactivity profiles at 500-ft altitude over point sources, Powder River Basin, Wyoming.

by Stead and others (1952). Near a given deposit the flight records generally indicate very marked abnormal radioactivity on one flight line with the shape (steep slope and sharp peak) and amplitude of the curve suggesting a point source. However, on most records some evidence of abnormality exists on one or both adjacent lines, indicating that the surface area of the source is much greater than the area of visible ore outcrop and probably is finite in size, according to the definitions given above. This thesis was further supported by calculations of the grade-area of the sources, based upon the flight data. At several deposits the calculated values were much greater than the grade-area values based upon field observations, as the observed values are ordinarily contingent upon the extent of the deposit determined by visible uranium minerals or by obviously abnormal radioactivity.

The reason for the discrepancy between computed and observed values was found by means of isorad surveys at two localities (Figure 10) that showed an aura of slightly abnormal radioactivity extending for several tens to more than a hundred ft from the loci of visible mineralization. The radioactivity is not sufficiently intense to be detected easily unless systematic surveys are made. It is not known whether the aura represents a weakly mineralized zone surrounding the locus of maximum concentration, or whether it is a weathering and erosion phenomenon whereby fragments of the higher grade material are carried laterally by these processes. The aura definitely contributes to the radiation intensity recorded in the air and must therefore enter into calculation of the grade-area product. Moreover, it is indeed doubtful that many sandstone-type uranium deposits would have been found from the air were it not for the extensive radioactive aura.

Two radiation profiles that typify point source behavior are shown in Figure 11.

As the anomaly resulting from a point source is recorded on only one flight line, it is possible to determine from equation (4) the minimum grade-area product of the source, but little can be learned of the source position. The geographic location of the peak intensity fixes the position of the source in the direction of flight, that is, the center of the source lies along a line normal to the flight path through the peak-intensity position. The location of the center normal to flight direction may be at any distance from 0 to 750 ft from the flight line.

Radioactivity profiles recorded at 500-ft altitude over the two uranium deposits mentioned above are shown in Figure 11. Two flights were made over anomaly 50–55.1 and three were made over 60–22.2. Equation (4) was used to determine the grade-area of the sources. Prospect pits were visible on the ground, and the flight path was observed to be nearly directly over the deposits, so that $r=x$.

The flight data, results of computation, and the observed data are tabulated below:

| *Anomaly* | *I* | *H* | *Grade-area (equation 4)* | *Average grade-area (equation 4)* | *Grade-area (observed)* |
|---|---|---|---|---|---|
| 50–55.1 | 660 | 3,250 | $9.50\times10^3$ | $5.99\times10^3$ | $1.4\times10^3$ |
| 50–55.1 | 430 | 1,890 | 2.48 | | |
| 60–22.2 | 580 | 3,260 | 9.95 | $8.10\times10^3$ | $3.0\times10^3$ |
| 60–22.2 | 440 | 2,270 | 5.50 | | |
| 60–22.2 | 630 | 3,350 | 8.85 | | |

The spread in the airborne data probably is typical of what one may expect from point sources. Comparison of the calculated data with the observed values show the calculated values to be consistently high. At the maximum deviation from the observed figure, the airborne data are high by a factor of about seven.

## SURVEYS FOR PETROLEUM

A report on airborne radioactivity surveys in geologic exploration could not omit reference to the relation of radioactivity to oil and gas fields that has been the subject of many papers in the last few years.

Nearly all of the airborne radioactivity surveys made by the U. S. Geological Survey have been undertaken on behalf of the Atomic Energy Commission and the primary objective of the surveys was the exploration for radioactive minerals. Flights over petroliferous areas were made only incidentally to the stated objective, and the flight data were not compiled in such a manner that intensive study with respect to the petroleum problem could be made. Examination of the relatively few data that were obtained did not show obvious characteristics that were diagnostic of, or could be related to, the occurrence of petroleum. However, our experience in this aspect of airborne surveys to date is quite limited, and we certainly are not in a position to take a dogmatic view at this time.

## SUMMARY AND CONCLUSIONS

The results of the present study indicate that, in general, the adequacy of

an analysis of airborne radioactivity survey data will depend upon the geometric and geologic complexity of the source and the areal extent of the source.

It is obvious that, as the source geometry departs from a simple configuration, the difficulty in interpretation becomes greater. The same applies to the distribution of radioactive materials within the source. Homogeneous material of simple geometry will yield a generally distinctive curve while complex geometries and a heterogeneous distribution of radioactive materials within the source tend to obscure and override the diagnostic characteristics.

In addition to their obvious value in exploration for uranium, aerial surveys can provide useful information in exploration for beach placers, both modern and ancient, and for marine phosphate deposits.

The results further indicate that, where quarter-mile linespacing and 500 ft ground clearance are used the eU content of homogeneous infinite sources can be determined perhaps to within a few thousandths of a percent and the source boundary can be placed within a few hundred ft. At the other extreme, the grade-area of a point source under ideal conditions can be determined within a factor of about five, but little can be learned of either specific parameter. The results of analyses of simple finite and slab sources will probably fall somewhere between the two extremes of infinite and point sources.

In dealing with what are obviously complex source conditions it is essential that all available geologic information be utilized in order to choose the most logical mode of analysis.

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GEOPHYSICS, VOL. XXV, NO. 2 (APRIL, 1960), PP. 433-444, 9 FIGS.

# EFFECT OF PORE FLUIDS ON THE ELASTIC PROPERTIES OF SANDSTONE*

R. L. MANN† AND I. FATT‡

## ABSTRACT

Bulk compressibility, Young's modulus, and Poisson's ratio were measured on three sandstones. Measurements were made on both dry and water saturated samples. Several runs were made on each sandstone to establish the statistical validity of the differences observed between the wet and dry samples. Bulk compressibility of wet sandstone was 10 to 30 percent greater than for dry. Young's modulus was 8 to 20 percent less for wet sandstone, and Poisson's ratio was 100 percent greater on one type of sandstone when wet and only slightly greater or about the same on wet samples of the others. A high clay content is believed to lead to a large effect of water on the elastic moduli of sandstone.

## INTRODUCTION

Laboratory measurements of the elastic constants of porous rock are often made on dry samples and the data are then applied to formations containing liquids. Aqueous solutions in the pore spaces would be expected to have some influence on the elastic properties, but little information of this kind has been reported (Wyllie, 1958). The elastic constants of wet and dry rock, measured under static conditions, are reported in this paper. If pore liquids change elastic constants, velocity in the liquid-saturated rock will be influenced not only by conduction through the liquid present, but also because of the action of the liquid on the rock.

Three quarried sandstones, readily available in large quantitites, were used for this investigation. Young's modulus, Poisson's ratio, and the bulk compressibility in the range 0 to 20,000 psi were measured on wet and dry samples. A large number of runs were made on a sufficient number of samples to establish the precision of the data.

## EXPERIMENTAL PROCEDURE

### *Bulk Compressibility*

*Preparation of Cores.*—Cores of Berea, Boise, and Bandera sandstone were drilled perpendicular to the bedding plane with a three-quarter inch internal diameter diamond core drill using water as a coolant. The cores were then cut off to five inches in length and oven dried at 250°F. for about 24 hours. The cores were marked, the length measured, and then placed in a desiccator until used.

*Mounting.*—Several runs were made with the core mounted in a thin copper foil jacket. The method did not prove satisfactory for cores having large pore

* Taken in part from M.S. thesis, by R. L. Mann, submitted to the Graduate Division, University of California, Berkeley, June 1959. Presented at the twenty-ninth Annual Meeting, Los Angeles, November 10, 1959. Manuscript received by the Editor July 28, 1959.

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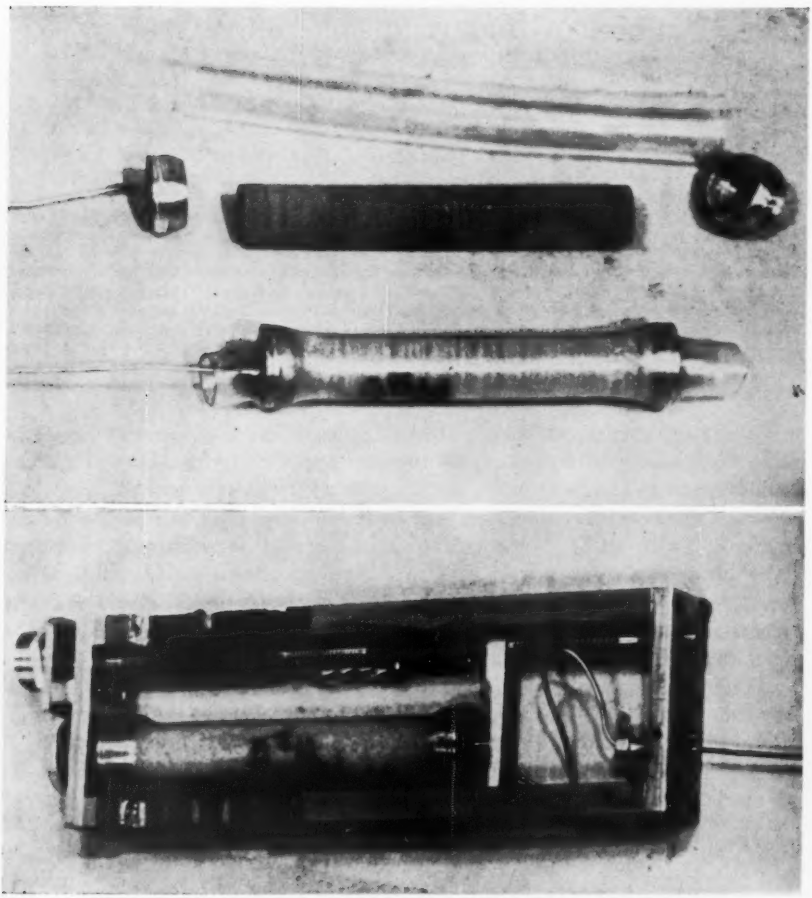

FIG. 1. Above: Core, plastic sleeve, and end cap shown above. Below: Mounted core in deformation measuring apparatus.

openings at the surface. An improved mounting technique using a plastic sleeve was developed. Brass end caps, shown in Figure 1, were fitted over the ends of the core, then a three-quarter inch shrink fit plastic sleeve was placed over both the core and end caps. The plastic sleeve used was three-quarter inch Jayco-60 tubing, manufactured by the Jorden Manufacturing Co., Desplaines, Ill. This tubing can be dilated in a General Electric 12501 dilator for easy mounting. The sleeve dilates to approximately 35 percent of its original diameter. The sleeve required 12 hours at room temperature to shrink to normal size, making a tight seal around the core and end caps.

One of the brass end caps had a one-eighth inch high pressure tubing mounted in its end to allow the pore pressure of the jacketed core to be vented to atmospheric pressure and thus be independent of the applied hydrostatic load.

*Saturating.*—Cores to be run with liquid in the pore spaces were placed in a vacuum desiccator (before mounting the sleeve on the core), evacuated to 0.1 to 0.2 mm of mercury (absolute), and the saturating fluid introduced into the desiccator and allowed to enter the core. The vacuum was then released and the core mounted as before. By this procedure the core was made essentially one hundred percent saturated.

*Measurements.*—The apparatus used in this investigation has been described previously (Fatt, 1958; Mann, 1959). Essentially, it is a device for measuring linear deformation of the cylindrical core under hydrostatic stress. It consists of a stainless steel frame that holds the five inch core and a follower arm that rests on the core, and in turn changes the resistance of a linear potentiometer, mounted on the steel frame, as the core changes in length. The resistance of the potentiometer was read on a Leeds and Northrup resistance bridge type 4760. A Foxboro recorder simultaneously recorded the resistance changes to obtain a positive indication of deformation equilibrium of the core.

The linear deformation can be related to the bulk compressibility by the equation,

$$C_b = \frac{3}{L}\frac{dL}{dp}. \tag{1}$$

$dL/dp$ was obtained by graphically differentiating the linear deformation vs pressure curve.

Ninety bulk compressibility measurements were made on a total of 38 specimens. Twelve calibration runs were made on three standardizing materials; calcium, barium, and aluminum. The compressibility of the standards were reproducible to an average mean deviation of 1.07 percent, with a maximum deviation of 2.7 percent from the mean. If the compressibilities given by Birch (1942) are taken as the standard, then the measured compressibilities of the sandstones are accurate to within 2.7 percent.

### *Young's Modulus and Poisson's Ratio*

*Preparation of Cores.*—The three types of sandstone were cored perpendicular to the bedding plane with a two inch internal diameter diamond core drill. The cores were cut to five inches in length and oven dried at 250°F. for 24 hours.

The Young's modulus and Poisson's ratio were measured simultaneously by the devices shown in Figures 2 and 3. Both devices were on the sample while the measurement was being made.

The Young's modulus apparatus was equipped with a dial indicator that could be read to 0.0001 inch. The lever arm gave a twofold multiplication over a three inch gauge length. The instrument was sensitive to strains of about 16

FIG. 2. Thin-sections of sandstones.

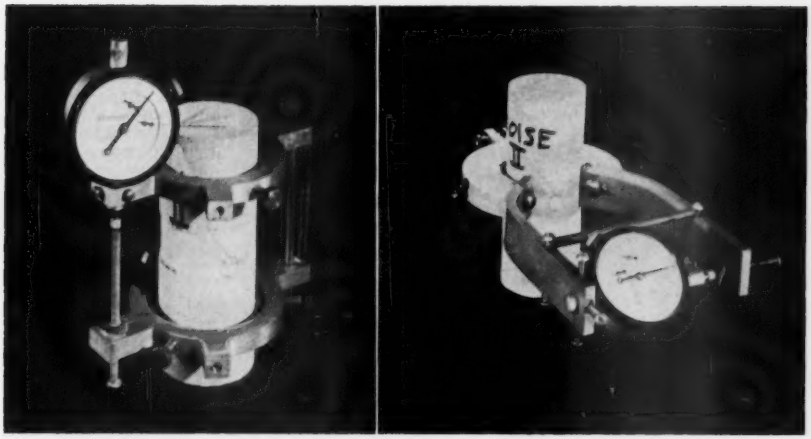

FIG. 3. Left: Young's modulus apparatus. Right: Poisson's ratio apparatus.

microinches per inch. The cores were loaded in a hydraulic press at a rate of about 1,000 psi per minute.

Poisson's ratio was calculated from the lateral strain induced by an axial stress. This datum was obtained by measuring the change in the diameter of the two inch diameter specimen. A dial gauge that read to 0.0001 inch was mounted on a lever arm that multiplied the lateral deflection by 3.6. A lateral strain of 14 microinches per inch could be recorded with this apparatus. Poisson's ratio, $\sigma$, was then calculated from the two simultaneous measurements by the relationship:

$$\sigma = \frac{\text{lateral strain/unit axial stress}}{\text{axial strain/unit axial stress}}. \qquad (2)$$

*Sandstone Cores.*—Boise, Berea, and Bandera were the three types of sandstone used in this research. These are well consolidated sandstones, readily available,[1] and have fairly uniform characteristics. Table I is a detailed description of the sandstones. Figure 3 is a photograph of the magnified sandstone thin-sections.

The elastic limits were determined for each type of sandstone. The elastic limit for the bulk compressibility was determined by observing the maximum pressure that could be applied before permanent deformation of the core occurred. For Boise sandstone the limit was 10,000 to 14,000 psig, for Berea sand-

[1] Berea Sandstone: Cleveland Quarries Co., Amhurst, Ohio. Boise Sandstone: Boise Stone and Tile Co., 5106 Fairview Ave., Boise, Idaho. Bandera Sandstone: Bandera Stone Quarry, Redfield, Kansas.

TABLE I. DESCRIPTION OF SANDSTONES

| | Sandstone | | |
|---|---|---|---|
| | Boise | Berea | Bandera |
| Porosity, % | 26.5 | 20.5 | 20.0 |
| Permeability, md | 1,200–1,600 | 250 | 3.5 |
| bulk density (gms/cc) | 1.91 | 2.14 | 2.16 |
| grain density (gms/cc) | 2.60 | 2.69 | 2.70 |
| rock type | Feldspathic Graywacke | Feldspathic Sandstone | Feldspathic Graywacke |
| sorting | poor | medium | medium to good |
| roundness | subangular | subangular | subangular |
| sphericity | medium | medium to high | low to medium |
| matrix | silica, clay, sericite } 44% | calcite 1%; silica, sericite, clay } 27% | calcite 22%; silica, clay } 29% |
| grains | quartz, feldspar } 56% | quartz, feldspar } 72% | quartz, feldspar } 49% |
| remarks | fine grained | very fine grained | extremely fine grained |

stone, between 18,000 and 20,000 psig. The elastic limit for Bandera was above 20,000 psig.

The elastic limit for the three sandstones under simple axial load was determined by stressing three-quarter inch diameter cylinders of the sandstone to failure. The elastic limit under uni-axial compression for Boise was 5,000 psig, for Berea 6,000 psig, and for Bandera 7,000 psig, all $\pm 500$ psig.

The initial runs for each of the three sandstones gave a higher bulk modulus, and lower Young's modulus, than subsequent runs. It was also noticed that a 0.05 to 0.1 percent permanent deformation of the sample occurred only on the initial run. For this reason the data presented in this paper are for runs subsequent to the initial loading.

It was noticed by the authors, and previous investigators, that a hysteretic loop occurs in the deformation vs pressure plot for both uni-axial and tri-axial loads. It is for this reason that the elastic moduli data are reported only for the compressional part of the cycle.

## RESULTS

The elastic constants for the three sandstones, wet and dry, the standard deviation, and the number of runs are given in Table II.

Typical plots of the deformation vs load are given in Figures 4 through 9.

## DISCUSSION OF RESULTS

### *Bulk Compressibility*

The bulk compressibility was measured on samples which were dry and on others which were saturated with 1N $AlCl_3$, 2N NaOH, and distilled water. The results did not appear to depend upon the type of ion in solution but merely on

TABLE II

| Sample | $E$, psi | $\sigma$ | $C_b$ psi$^{-1}$ |
|---|---|---|---|
| *Boise Dry* | | | |
| No. of Runs | 4 | 4 | 7 |
| Avg Value | $2.85 \times 10^6$ | 0.264 | $0.723 \times 10^{-6}$ |
| Std. Deviation | $0.000 \times 10^6$ | 0.012 | $0.053 \times 10^{-6}$ |
| *Boise Wet* | | | |
| No. of Runs | 4 | 4 | 10 |
| Avg Value | $2.42 \times 10^6$ | 0.255 | $0.867 \times 10^{-6}$ |
| Std. Deviation | $0.000 \times 10^6$ | 0.013 | $0.113 \times 10^{-6}$ |
| *Berea Dry* | | | |
| No. of Runs | 8 | 8 | 8 |
| Avg Value | $2.84 \times 10^6$ | 0.242 | $1.06 \times 10^{-6}$ |
| Std. Deviation | $0.020 \times 10^6$ | 0.010 | $0.102 \times 10^{-6}$ |
| *Berea Wet* | | | |
| No. of Runs | 8 | 8 | 10 |
| Avg Value | $2.66 \times 10^6$ | 0.277 | $1.140 \times 10^{-6}$ |
| Std. Deviation | $0.085 \times 10^6$ | 0.016 | $0.110 \times 10^{-6}$ |
| *Bandera Dry* | | | |
| No. of Runs | 7 | 7 | 6 |
| Avg Value | $1.84 \times 10^6$ | 0.174 | $0.836 \times 10^{-6}$ |
| Std. Deviation | $0.170 \times 10^6$ | 0.021 | $0.022 \times 10^{-6}$ |
| *Bandera Wet* | | | |
| No. of Runs | 8 | 8 | 10 |
| Avg Value | $1.49 \times 10^6$ | 0.387 | $1.055 \times 10^{-6}$ |
| Std. Deviation | $0.010 \times 10^6$ | 0.007 | $0.065 \times 10^{-6}$ |

the presence of water. The sandstones exhibited about 10 percent to 30 percent increase in bulk compressibility when an aqueous solution was present in the pore space.

The compressibility was a function of pressure in the range of 0 to 6,000 psig indicating that all three sandstones deviated from ideal elastic bodies at low pressures. Above 6,000 psig the compressibility was constant.

*Young's Modulus and Poisson's Ratio*

The axial stress vs axial strain curves, shown in Figures 7 through 9, did not have a constant slope below 2,000 psi. This was probably a result of the granular nature of sandstone. In the initial unstressed state the grains are probably in point contact; as the load is applied to the rock the stress at these point contacts is much greater than is indicated by the applied load. As the load is increased further, more grain area comes into contact thereby relieving the high stress in these areas. Young's modulus and Poisson's ratio are reported only over the portion of the deformations vs stress curve where the slope is constant.

The presence of water in the pore spaces of the sandstones caused Young's modulus to decrease and Poisson's ratio to increase, or remain the same.

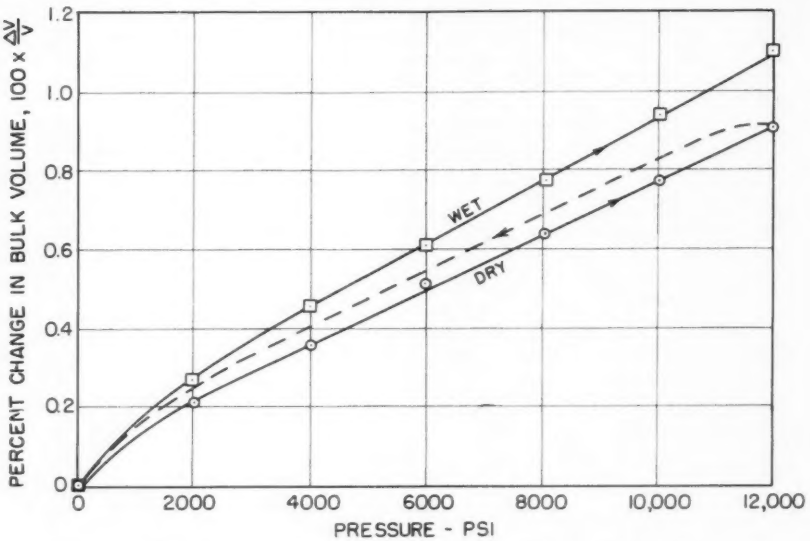


FIG. 4. Change in bulk volume as a function of pressure for wet and dry Boise sandstone.

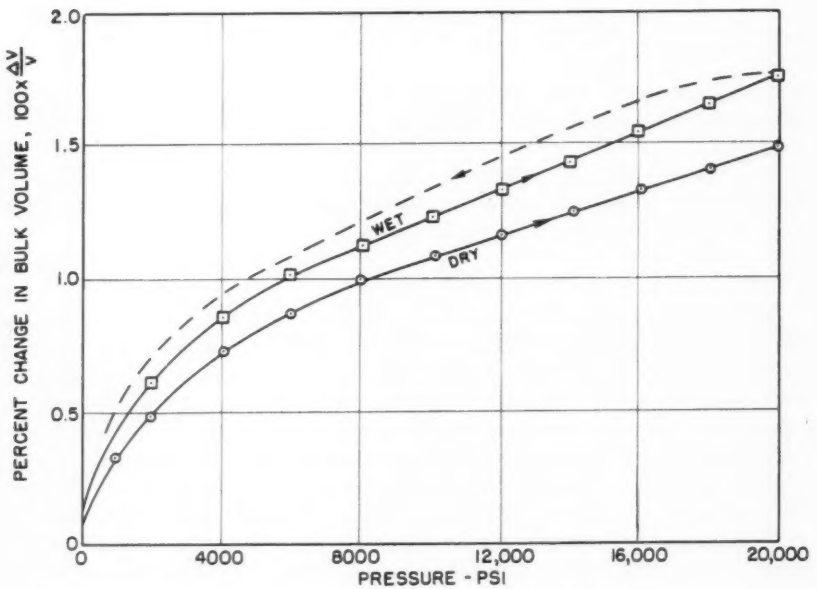


FIG. 5. Change in bulk volume as a function of pressure for wet and dry Berea sandstone.

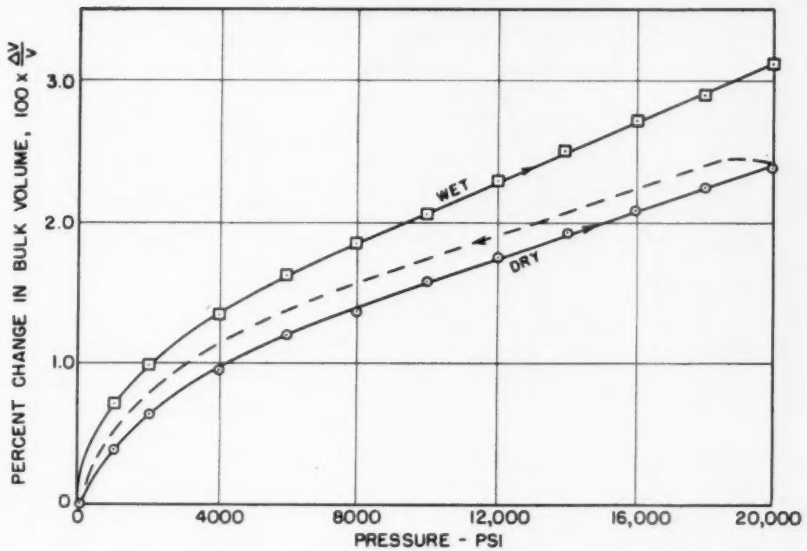


FIG. 6. Change in bulk volume as a function of pressure for wet and dry Bandera sandstone.

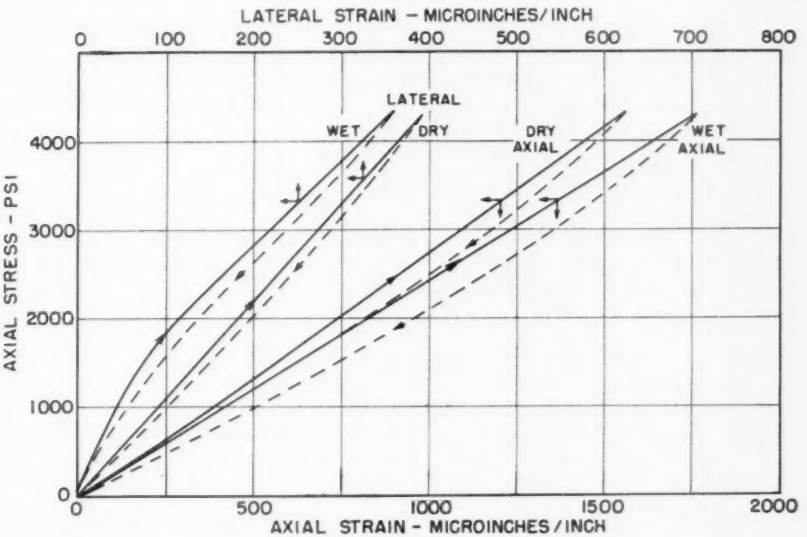


FIG. 7. Axial and lateral strain of wet and dry Boise sandstone under axial stress.

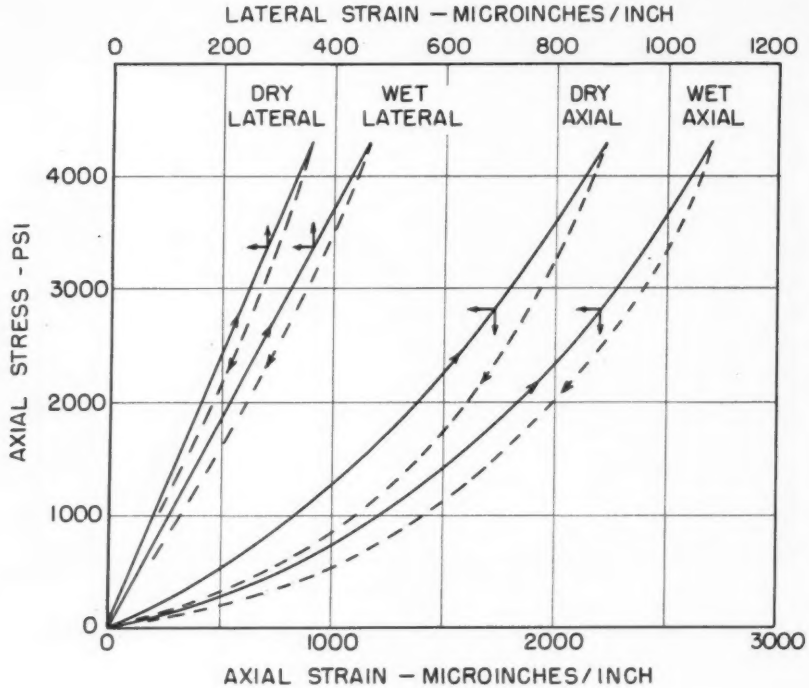


FIG. 8. Axial and lateral strain of wet and dry Berea sandstone under axial stress.

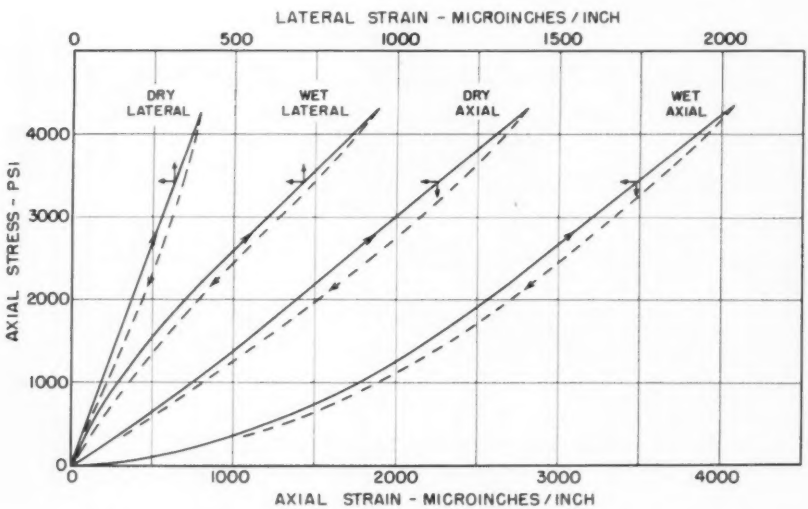


FIG. 9. Axial and lateral strain of wet and dry Bandera sandstone under axial stress.

TABLE III

| Rock | $\frac{E}{\text{psi}}$ | $\sigma$ | $C_b$ psi$^{-1}$ | $\frac{EC_b}{1-2\sigma}$ |
|---|---|---|---|---|
| Ideal elastic body | | | | 3.0 |
| Boise Dry | $2.85\times10^6$ | 0.264 | $0.723\times10^{-6}$ | 4.36 |
| Boise Wet | $2.42\times10^6$ | 0.255 | $0.90\times10^{-6}$ | 4.44 |
| Berea Dry | $2.84\times10^6$ | 0.242 | $1.06\times10^{-6}$ | 5.83 |
| Berea Wet | $2.66\times10^6$ | 0.277 | $1.13\times10^{-6}$ | 6.74 |
| Bandera Dry | $1.84\times10^6$ | 0.174 | $0.84\times10^{-6}$ | 2.37 |
| Bandera Wet | $1.49\times10^6$ | 0.387 | $1.06\times10^{-6}$ | 7.07 |

The amount of clay in the sandstone appeared to influence Poisson's ratio to a high degree. Bandera sandstone, with about 25 to 30 percent clay, showed a twofold increase in Poisson's ratio when the sandstone was saturated with water. In Young's modulus and Poisson's ratio tests, only water was used as a saturating liquid.

The classical theory for an ideal elastic body predicts that for small strains the elastic moduli will be independent of stress and that bulk compressibility, Young's modulus, and Poisson's ratio will be related by the equation:

$$EC_b = 3(1 - 2\sigma). \tag{3}$$

The deformations vs stress curves in Figures 4 through 9 show that the slope, and therefore the elastic moduli, are not independent of stress at low stress. At higher stress the slopes do become constant.

The validity of equation (3) for dry and wet sandstones was tested by using the elastic moduli from the constant slope portion of deformation vs stress curves. For an ideal elastic body

$$\frac{EC_b}{1 - 2\sigma} = 3 \cdot \tag{4}$$

Table III shows that even at the highest stress conditions of this investigation, sandstones deviate from ideal behavior. Furthermore, Table III shows that equations (3) or (4) do not allow prediction of the direction or magnitude of the changes in elastic moduli caused by pore liquids.

## CONCLUSIONS

1. The presence of an aqueous solution in the pore spaces of three different sandstones caused the elastic constants to change.
   - A. Bulk compressibility increased by 10 percent to 30 percent.
   - B. Young's modulus decreased by 8 percent to 20 percent.
   - C. Poisson's ratio increased by one hundred percent for Bandera, and changed only a small amount for the other two sandstones.

2. The sandstone with the largest amount of clay exhibited the greatest change in its properties when saturated with an aqueous solution.
3. The ideal elastic equation is not valid for the sandstones studied.

ACKNOWLEDGMENT

The authors thank the California Research Corporation for a research grant in support of this work, and Wayne S. Cavender for his technical assistance.

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GEOPHYSICS, VOL. XXV, NO. 2 (APRIL, 1960), PP. 445–450, 1 FIG.

# PHOTOGRAMMETRIC DETERMINATION OF ELEVATIONS FOR REGIONAL GRAVITY SURVEYS*

W. T. KINOSHITA† AND B. H. KENT†

## ABSTRACT

Precision photogrammetric methods were used to obtain elevations of gravity stations in an area in the southern Sierra Nevada and in west-central Idaho. In both areas, relief is more than 3,000 ft and in the Idaho area there is also a dense cover of forest and brush.

In addition to photogrammetric determinations of gravity station elevations in the Idaho area, 55 photogrammetric elevations were determined for ground points that had been established previously by topographic surveys. A statistical analysis of the differences between photogrammetric and known ground elevations indicated that the mean of the errors is −0.2 ft; 71 percent of the photogrammetric errors are included within one standard deviation (3.4 ft), and 96 percent of the errors are included within twice the standard deviation (6.8 ft).

The photogrammetric combination used in both areas was the multiplex stereoscopic plotting instrument and 1:49,500 scale photography taken with a 6-inch focal length lens. It is probable that smaller standard deviations can be obtained by combining larger scale photography with more precise stereoscopic plotting instruments.

## INTRODUCTION

If reliable gravity station elevations can be obtained from aerial photographs, photogrammetry can provide a convenient and economical way to obtain ground control for regional gravity surveys. Field conditions such as excessive relief, rugged terrain, or dense vegetation, which make conventional survey methods slow and costly, make this possibility particularly attractive.

Elevations of 13 gravity stations in an area in the southern Sierra Nevada were determined photogrammetrically in May, 1957 by C. H. Sandberg and B. H. Kent, both of the U. S. Geological Survey, in conjunction with the regional gravity studies of Howard Oliver, also of the Survey, in the southern Sierra region. When the photogrammetrically-determined elevations were checked later by altimeter and direct-leveling methods, maximum errors on the order of ±10 ft were indicated. These results were considered sufficient for the requirements of the survey.

A second, similar series of tests conducted in the fall of 1957 are described in this paper. Elevations of 19 gravity stations in an area in Idaho were determined photogrammetrically in October, 1957. Gravity readings at these stations had been made the previous month as part of a regional gravity survey of the Long Valley area in the Cascade and Smith's Ferry 15-minute quadrangles. This area has 3,000 ft of relief, a rugged terrain, and a dense cover of trees and brush.

To provide sufficient data for a statistical analysis, photogrammetric elevations of 55 ground points were determined, in addition to the 19 gravity stations. Elevations of these ground points had been established previously by

* Publication authorized by the Director, U. S. Geological Survey, Manuscript received by the Editor April 29, 1959.

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field surveys. An analysis was made of the differences between photogrammetric elevations and known ground elevations to evaluate the quality of elevation control obtained from aerial photographs.

## PHOTOGRAMMETRIC DATA

In photogrammetric work, stereoscopic plotting instruments are used in order to recover at model scale the true geometric relationships between the camera, camera stations, and the ground surface. The multiplex projector was selected for these tests.[1] The multiplex instrument projects two photographic diapositives in such a manner as to form a true model image of a portion of the earth's surface in which all three dimensions are represented at true scale and can be measured. Vertical dimensions are measured by means of a calibrated multiplex tracing table. The scale of the multiplex tracing table used in these tests is in metric units, and the smallest unit is 0.1 mm; however, interpolations to less than 0.1 mm can be made.

In this paper, the scale model formed by simultaneous projection of two photographs is referred to as the "instrument model," and the smallest unit of measurement (0.1 mm) that can be read directly on the vertical scale of the tracing table used is referred to as a "base unit."

The scale of the photographs used in these tests resulted in a model scale of about 1:20,700 in multiplex projection. Thus, the net enlargement factor is about 2.4 times the original photographic scale. However, individual models were not adjusted to a common scale and, therefore, model scales differed slightly one from another.

Diapositives and photographic prints used for control in these tests were those originally used to compile the Cascade and Smith's Ferry 15-minute quadrangles. Basic ground control obtained by topogrpahic surveys was recorded on these photographs. In addition, an identical set of photographic prints on which the gravity stations were plotted was available for the gravity survey.

## PHOTOGRAMMETRIC MEASUREMENTS

Standard methods of orienting multiplex instrument models and leveling them to vertical ground control were followed in all testing procedures, except that individual models were not adjusted to a common scale. Ground points common to both the instrument model and the topographic map were identified and noted in each case. Distances between corresponding sets of points were then measured, and the horizontal scale of the instrument model was determined. The vertical scale of an undistorted instrument model is the same as the horizontal scale.

[1] The writers recognize the well-known fact that the multiplex stereoplotting instrument is the least accurate of the photogrammetric plotting instruments commonly available. The decision to use it, however, was made because all of the necessary data and materials required to make the test were immediately available at no cost to the project, and the multiplex met the accuracy requirements for the Long Valley Survey.

Measurements in the vertical direction were made in base units and then converted to their equivalent values in ft. A base unit on the instrument model represents 6.8 ft of elevation on the ground when the scale is 1:20,700.

At least three ground-control points established by previous field surveys were selected for initial leveling of each instrument model. By averaging a series of ten or more interpolated readings, the model was adjusted until the vertical control points read correctly to a precision of the base unit. Additional ground-control points were identified on the instrument model and designated as "check points." The average of a series of interpolated readings for each of the check points was used to establish the photogrammetric elevation for each of these points. In addition to providing statistical data, these photogrammetric elevations also served to indicate the amount of distortion still present in each instrument model.

Photogrammetric elevations of the 19 gravity stations were determined in the same manner after data on check point readings were obtained.

## ANALYSIS OF DATA

Elevations of 55 check points were determined for eight instrument models; the elevation of each of these points had been established by ground-survey methods. Any disagreement between a photogrammetric elevation and a previously established surface-elevation for the same point was considered to be a photogrammetric error.

A statistical analysis of errors in the photogrammetric elevations was made for 51 of these check points (Hoel, 1954). Four of the 55 check points were on the extreme edges of the instrument models. Their photogrammetric elevations were in error respectively by $-17$, $-19$, $-23$, and $-25$ ft. Negative errors are to be expected on the extreme edges of an instrument model. This results from the normal distortion characteristic of multiplex instrument models. For this reason these four errors were not included in the analysis, although they are included in the histogram (Figure 1).

In constructing the histogram (Figure 1) the errors were indicated as "plus" or "minus" with respect to known surface elevations. The error class is one ft, and the width of each column represents errors that fall in a particular one-ft interval. The height of each column represents the number of errors that fall in each class.

In the histogram, the mean error is $-0.2$ ft. The standard deviation from this mean is 3.4 ft and twice the standard deviation is 6.8 ft. Of the total number of errors (51), 71 percent fall within the interval $-3.6$ to $+3.2$ ft, and 96 percent fall within the interval $-7.0$ and $+6.6$ ft.

A distribution is considered "normal" (e.g. a sufficient number of samples) if the standard deviation includes 68.2 percent of that distribution. The limited number of points sampled and measured, plus "borderline" errors, have probably contributed to the favorable results obtained in these tests. Results in 71 percent of the points tested are significantly better than other empirical multi-

| X | $f_i$ | $X_i f_i$ | $(X_i-\bar{X})$ | $(X_i-\bar{X})^2$ | $f(X_i-\bar{X})^2$ |
|---|---|---|---|---|---|
| + 7 | 2 | +14 | +7.22 | 52.13 | 104.26 |
| + 6 | 1 | + 6 | +6.22 | 38.69 | 38.69 |
| + 5 | 3 | +15 | +5.22 | 27.25 | 81.75 |
| + 4 | 2 | + 8 | +4.22 | 17.81 | 35.62 |
| + 3 | 3 | + 9 | +3.22 | 10.37 | 31.11 |
| + 2 | 2 | + 4 | +2.22 | 4.93 | 9.86 |
| + 1 | 5 | + 5 | +1.22 | 1.49 | 7.45 |
| 0 | 9 | 0 | +0.22 | 0.05 | 0.45 |
| − 1 | 6 | − 6 | −0.78 | 0.61 | 3.66 |
| − 2 | 7 | −14 | −1.78 | 3.17 | 22.19 |
| − 3 | 4 | −12 | −2.78 | 7.73 | 30.92 |
| − 4 | 3 | −12 | −3.78 | 14.29 | 42.87 |
| − 5 | 1 | − 5 | −4.78 | 22.85 | 22.85 |
| − 6 | 1 | − 6 | −5.78 | 33.41 | 33.41 |
| − 7 | 1 | − 7 | −6.78 | 45.97 | 45.97 |
| −10 | 1 | −10 | −9.78 | 95.65 | 95.65 |
| | 51 | −11 | | | 606.71 |

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{h} X_i f_i$$

$$\bar{X} = \frac{1}{51}(-11)$$

$$\bar{X} = 0.22\ \text{ft. (Mean)}$$

$$S = \sqrt{\frac{1}{n}\sum_{i=1}^{h}(X_i - X)^2 f_i}$$

$$S = \sqrt{\frac{1}{51}(606.71)}$$

$$S = \pm 3.4\ \text{ft. (Standard Deviation)}$$

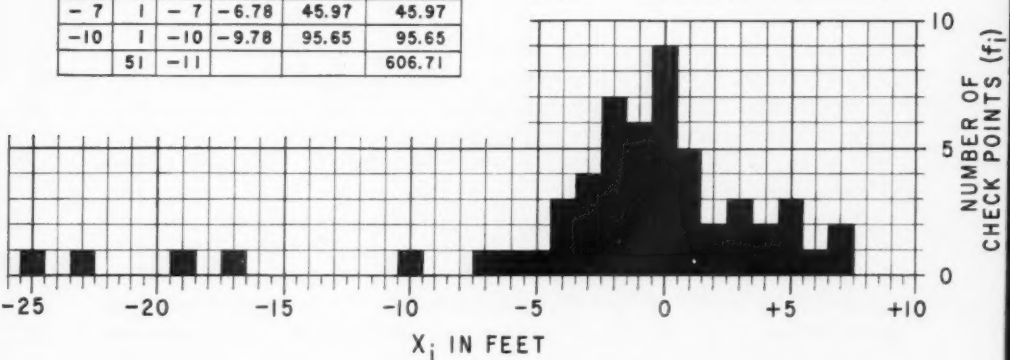


FIG. 1. Histogram of distribution of errors for 55 check points.

plex data compiled for topographic maps. However, the indicated error for 96 percent of the points measured (a percentage that is in harmony with the "normal") does agree with the order of accuracy that might be expected with multiplex equipment under special test conditions. Nevertheless, this order of accuracy is considered to be about twice the accuracy that may be expected under normal operating conditions.

In these tests, the shape of the histogram indicates a random distribution of error. With the exception of the four large "minus" errors previously noted, and the nine errors in the "zero" class, there were 24 "minus" errors and 18 "plus" errors. Photogrammetric readings on closely spaced check points in the instrument models were alternately "plus" and "minus," with respect to the corresponding surface elevations. No marked trend toward either "plus" or "minus" readings was observed in any of the instrument models. This random distribu-

tion of errors and the absence of marked trends would seem to indicate that the significance of errors due to the presence of distortion in the instrument models was subordinate to errors in the reading procedure. Since a certain amount of optical distortion is present in every instrument model which would be variable, its presence would probably be indicated by marked trends toward "plus" or "minus" readings. Detection and evaluation of such distortions would also depend upon the distribution and the quality of control data available, and upon the nature of the equipment used.

Each of the eight instrument models had a slightly different scale, however, all eight were approximately 1:20,700. The equivalent value of a base unit in each was, therefore, about 6.8 ft, which is twice the standard deviation.

The practical value of interpolation to less than one base unit is indicated by the results of the analysis: seventy one percent of the errors fall within the standard deviation ($\pm 3.4$ ft) and this deviation is about one-half of a base unit.

## CONCLUSIONS

With respect to the ground-control, photogrammetric elevations of 96 percent of the 51 check points in this test area were found to have errors not exceeding 6.8 ft. It is probable that the same order of error is to be expected in the photogrammetric elevations determined for the 19 gravity stations.

For the eight multiplex instrument models involved in these tests the average equivalent value of a base unit (0.1 mm) was 6.8 ft. The coincidence between twice the standard deviation (6.8 ft) and this average equivalent base unit may be significant. However, only one photogrammetric combination, 1:49,000 scale photography and a multiplex stereoscopic plotting instrument, was tested. Further tests, preferably of other photogrammetric combinations, are needed in order to determine whether this relationship between the average equivalent value of a base unit and two times the standard deviation is coincidental or significant.

Other stereoscopic plotting instruments, such as the ER-55, Kelsh, and Universal plotters, are known to be more precise than the multiplex plotting instrument. All of these plotters provide a larger instrument model scale than does the multiplex. Since the equivalent value of a base unit varies inversely with the scale of an instrument model, it would be expected that smaller standard deviations would result from any combination of these other, more precise, stereoplotting instruments with larger scale photography. We believe that it is possible, and therefore practical with the more accurate plotting instruments, to obtain reliable supplemental ground-control data well within the general accuracy range of plus or minus four to ten ft by photogrammetric methods.

No meaningful cost comparisons between the photogrammetric and ground survey methods can be made on the basis of the test made in the Long Valley area. Here, suitable aerial photography and basic ground control were available at no cost from previous topographic surveys, and the only expense was a few

hours of photogrammetric work. The feasibility of using photogrammetry for regional gravity surveys in other areas depends mainly on the availability of suitable aerial photos, ground-control, and gravity station density required.

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GEOPHYSICS, VOL. XXV, NO. 2 (APRIL, 1960), PP. 451–467

# SOUND SPEED AND ABSORPTION STUDIES OF MARINE SEDIMENTS BY A RESONANCE METHOD*

## PART I

GEORGE SHUMWAY†


## ABSTRACT

Laboratory measurements of compressional sound speed, and absorption, have been made on 111 unconsolidated marine sediment samples, ranging from shallow water sands to deep-sea clays. In addition, determinations were made of porosity, wet density, and grain size distributions. Frequencies between 20 kc/sec and 37 kc/sec were used for the acoustic studies.

Sound speed values at room temperature range from 1.474 km/sec for a red medium clay to 1.785 km/sec for a medium sand. More than one-third of the values are lower than the value for sea water alone. Variations in the speed of sound in unconsolidated sediments as found in nature are caused by the following factors, in order of importance: (1) porosity, because of the great difference in compressibility of water and mineral grains; (2) the factor which produces rigidity, which appears to be related to the abundance of coarse grains; (3) pressure; (4) temperature; (5) compressibility of the grain aggregate, determined from compressibilities of individual minerals.

Sound absorption measurements ranged from 0.5 db/m for a medium clay (28.4 kc/sec) to about 20 db/m for silts and fine sands (between 30 and 37 kc/sec). An absorption maximum occurs for sediments of intermediate porosity (0.45–0.6) and intermediate grain size (0.031 mm–0.25 mm). The expression $\alpha = MA_s$, where $\alpha$ is the linear absorption coefficient, $M$ is a frequency-dependent factor related to the sediment volume fraction of grains in mutual contact, and $A_s$ is a computable total acoustically effective grain surface area, predicts the absorption values and the absorption maximum.

Absorption measurements at more than one frequency between 20 kc/sec and 37 kc/sec were obtained for 65 samples. Assuming that absorption is directly proportional to frequency raised to a power $n$, the data yield an average value of $n$ equal to 1.79, with a standard deviation of 0.98.


## INTRODUCTION

The general sediment, as found in nature, is a mixture of water, ions, colloidal particles, and mineral grains. Many particles, particularly those of clay and silt size, essentially are in suspension, while others, particularly those of sand size, are in contact with one another. Each particle has an irregular shape. Although certain minerals predominate in sediments, each sediment sample has a unique mineral grain composition. The acoustic properties of sediments are determined by such properties as these, and any general theory for acoustic wave propagation in sediment-like mixtures must account for these variables in one way or another. Experimental data concerning the acoustic properties of sediments and their relations to other physical properties are not abundant. The difficulties of developing useful acoustic theory for sediments make it necessary to have an ample body of experimental data at hand for checking and guiding the theoretical developments.

This study presents compressional sound speed and sound absorption data for 111 unconsolidated marine sediment samples, ranging from shallow-water

* This paper is a portion of a doctoral dissertation with the same title submitted to the University of California at La Jolla (1958). Manuscript received by the Editor May 14, 1959.

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sands to deep-sea clays. This suite includes most of the common marine sediment types, hence these measurements provide the general range of values to be expected for sea floor sediments. Measurments of porosity and wet density were made also, and grain size distributions were determined.

Previously published studies of a similar nature have not involved such a large and varied group of sediments. Hamilton et al. (1956) in a study preliminary to the present one, measured sound velocity and absorption in a group of shallow-water sediments from the region of San Diego. Sutton et al. (1957) measured sound velocity and certain other physical properties in samples from 26 cores taken in the Atlantic Ocean from water depths between 840 m and 4,780 m. Only a few of their samples had median diameters in the sand range, and all of these were oozes with calcium carbonate contents higher than 85 percent. Sound velocities, and rarely, sound absorptions, have been measured in smaller groups of sediments by a number of workers. Mifsud (1953) made acoustic studies on sands in a laboratory tank. Paterson (1955, 1956) reported sound velocities for porous sands measured in the laboratory. Laughton (1954, 1955, 1957) studied the effects of hydrostatic pressure and compacting pressure on compressional velocity in a few ocean sediments. Busby and Richardson (1957) published some sound absorption data for water-filled sands.

## MEASUREMENT METHODS

Sound speed and sound absorption were measured by a resonance technique: for a non-rigid, compliant-walled cylinder, resonant frequency is directly proportional to sound speed, and mechanical $Q$ is inversely proportional to the linear absorption coefficient. Sediment samples were driven to resonance at frequencies between 20 kc/sec and 37 kc/sec while held in thin-walled cylindrical plastic (Lucite) containers 5.08 cm in diameter and 12.7 cm long with a wall thickness of about 0.89 mm. The sound speed measurements are considered accurate to $\pm 10$ m/sec in low-loss sediments (clays and fine silts), and to $\pm 15$ m/sec for other sediments. Measurements on a given sample are reproducible to within 1 m/sec. Pertinent theory for this resonant technique was developed by W. J. Toulis (1956). A description of the technique of measurement and an evaluation of the accuracy to be expected was given in an accompanying paper (Shumway, 1956).

Immediately after completion of the resonance measurements on a sample, the sample temperature was determined. Then the following steps were taken. The mass of wet sediment in the container and the container volume were determined, and from these wet density was obtained. On some samples the static shear strength was measured by D. G. Moore using his published technique (in press), with the sediment still in the container. Then the sediment was removed and placed in an oven at a temperature between 105°C. and 110°C. until water loss ceased. From the mass of water lost the sediment porosity was calculated. Lastly, standard methods were used to determine the grain size distribution: sieve for coarser sands; settling tube (Poole, 1957) for materials of intermediate

size; pipette for the finest materials. Cumulative frequency tables for grain size distributions for all of the samples are presented in the dissertation of which this study is a part (Shumway, 1958), so for the sake of brevity need not be included here.

## SEDIMENTS

### *Sampling techniques*

The acoustic measurements were made with the sample held in thin-walled cylindrical plastic containers. In shallow water, these containers were taken to the sea floor by SCUBA diving, and filled with sediment by gently pushing them into the bottom (Shumway, 1956, p. 309). In deeper water, sediments first were obtained by coring or dredging, and then the plastic containers filled from this material.

Diver sampling was done for water depths less than about 45 m. In addition to the fact that diver-sampling allows the sample to be initially collected in the plastic container, it is advantageous because the diver may pick a representative location for the sampling. Often considerable variation in sediment composition is found on the sea floor within a meter laterally, and within even a few centimeters vertically. In many such places on the continental shelves, and in harbors, a randomly taken core or grab sample could misrepresent completely the general environment.

### *Shallow-water (harbor and shelf) sediments*

The shallow waters of San Diego Bay and the adjacent continental shelf were readily available for sampling and for direct observation by diving, hence a large number of samples were taken there. The term "shallow-water" as used here means water shallow enough for diving, i.e. less than about 45 m.

In the preliminary studies reported by Hamilton et al. (1956), 33 shallow-water stations were made and a total of 67 individual samples were studied. An entirely new series of stations was made to provide samples for the present study. Twenty-six new shallow-water stations were made, with two samples generally being taken at each station, to give a total of 55 new shallow-water samples. A chart showing the location of the shallow-water samples from the San Diego area is kept on file by the Navy Electronics Laboratory and does not appear here for reasons of military security. The geologic nature of sediments of the San Diego region has been studied by Emery et al. (1952).

In Table Ia these samples are identified by a prefix of SD (denoting San Diego area) and PC (denoting Panama City, Florida), a station number, and a lower case letter to distinguish samples taken at the same station.

### *Intermediate depth (continental shelf, slope, and borderland) sediments*

Several suites of samples were obtained from waters of intermediate depth. One group of six samples came from the continental slope east of Point Barrow,

(*Text continued on page 464*)

TABLE Ia. ACOUSTIC, GEOLOGIC, AND PHYSICAL PROPERTIES OF SHALLOW-WATER SEDIMENTS
(Bay and shelf to 50 meter depth)

| Sample Number | Sediment Type | Median Diameter Phi (mm) | Mean Diameter Phi | Phi Deviation Measure | Wet Density | Porosity | Sound Speed, km/sec (Temp. ° C.) | Sound Absorption, db/ft at c/s | | Acoustic Surface Area, $m^2$/g wet sed. |
|---|---|---|---|---|---|---|---|---|---|---|
| SD35a | sandy coarse silt | 4.20 (.054) | 5.16 | 1.90 | 1.60 | .645 | 1.496 (19.0°) | 1.779<br>3.692 | 23,051<br>30,439 | .0434 |
| SD35b | sandy coarse silt | 4.10 (.058) | 4.93 | 1.68 | 1.65 | .605 | 1.512 (18.9°) | 1.667<br>3.708 | 23,038<br>30,612 | .0409 |
| SD35c | sandy coarse silt | 4.10 (.058) | 5.00 | 1.75 | 1.67 | .579 | 1.512 (19.1°) | 2.614<br>3.897 | 23,360<br>30,792 | .0437 |
| SD36a | clayey sandy coarse silt | 4.45 (.046) | 5.98 | 2.28 | 1.56 | .663 | 1.490 (19.2°) | 2.004<br>4.036 | 23,012<br>30,461 | .0403 |
| SD36b | sandy coarse silt | 4.45 (.046) | 5.83 | 2.02 | 1.64 | .696 | 1.526 (19.5°) | 1.559<br>3.516 | 23,038<br>30,558 | .0388 |
| SD37a | medium sand | 1.95 (.259) | 1.72 | 0.75 | 1.96 | .417 | 1.678 (23.6°) | 3.60 | 25,807 | .0146 |
| SD27b | medium sand | 2.00 (.250) | 1.89 | 0.62 | 1.94 | .432 | 1.785 (23.4°) | 5.72 | 31,406 | .0162 |
| SD38a | medium sand | 1.82 (.284) | 1.65 | 0.91 | 1.99 | .391 | 1.710 (22.4°) | 4.23 | 26,076 | .0129 |
| SD38b | medium sand | 1.30 (.407) | 0.97 | 0.96 | 2.00 | .393 | 1.725 (23.4°) | 3.19 | 26,470 | .0103 |
| SD39a | fine sand | 2.50 (.176) | 2.42 | 0.46 | 1.96 | .429 | 1.700 (22.2°) | 2.79 | 26,049 | .0187 |
| SD39b | fine sand | 2.12 (.230) | 1.90 | 0.22 | 1.95 | .481 | 1.695 (23.4°) | 2.73 | 25,975 | .0120 |
| SD40a | coarse silt | 4.25 (.053) | 5.14 | 1.99 | 1.64 | .630 | 1.510 (21.0°) | 2.922<br>3.873 | 23,286<br>31,205 | .0416 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| SD40b | coarse silt | 4.20<br>(.054) | 5.23 | 1.89 | 1.62 | .604 | 1.514<br>(21.0°) | 2.202<br>3.811 | 23,214<br>30,965 | .0445 |
| SD41a | medium sand | 1.64<br>(.320) | 1.31 | 1.07 | 1.995 | .388 | 1.735<br>(22.0°) | 4.17<br>2.90 | 23,435<br>26,443 | .0107 |
| SD41b | medium sand | 1.75<br>(.298) | 1.55 | 0.87 | 1.99 | .362 | 1.712<br>(22.0°) | 3.65<br>3.04 | 23,335<br>26,218 | .0120 |
| SD42a | fine sand | 2.92<br>(.132) | 3.37 | 1.20 | 1.82 | .493 | 1.548<br>(19.8°) | 6.81 | 31,445 | .0352 |
| SD42b | very fine sand | 3.14<br>(.114) | 3.65 | 1.40 | 1.81 | .498 | 1.550<br>(20.6°) | 6.38 | 31,576 | .0396 |
| SD43a | fine sand | 2.27<br>(.208) | 2.29 | 0.33 | 1.95 | .424 | 1.691<br>(22.8°) | 2.75<br>2.63 | 23,342<br>25,987 | .0169 |
| SD43b | fine sand | 2.27<br>(.208) | 2.30 | 0.27 | 1.94 | .429 | 1.696<br>(22.9°) | 2.51<br>2.78 | 23,257<br>26,013 | .0170 |
| SD44a | medium sand | 1.24<br>(.425) | 1.13 | 0.82 | 2.02 | .383 | 1.748<br>(22.1°) | 2.60<br>3.41 | 26,851<br>36,077 | .0090 |
| SD44b | medium sand | 1.78<br>(.290) | 1.69 | 0.51 | 2.03 | .397 | 1.748<br>(22.6°) | 3.16<br>4.55 | 26,949<br>36,546 | .0117 |
| SD45a | fine sand | 2.75<br>(.148) | 2.77 | 0.20 | 1.92 | .454 | 1.68<br>(21.4°) | 4.07 | 29,227 | .0219 |
| SD45b | fine sand | 2.71<br>(.153) | 2.75 | 0.20 | 1.92 | .458 | 1.67<br>(21.8°) | 3.88 | 29,338 | .0213 |
| SD46a | medium silt | 5.48<br>(.0225) | 6.63 | 2.42 | 1.42 | .745 | 1.484<br>(20.3°) | 2.63 | 30,179 | .0462 |
| SD46b | medium silt | 4.99<br>(.031) | 5.96 | 3.74 | 1.44 | .724 | 1.492<br>(20.9°) | 3.52 | 30,403 | .0467 |
| SD47a | sandy coarse silt | 4.03<br>(.061) | 4.74 | 1.91 | 1.69 | .578 | 1.530<br>(21.5°) | 3.04<br>4.16 | 23,457<br>31,070 | .0424 |
| SD47b | sandy coarse silt | 3.98<br>(.063) | 4.68 | 1.86 | 1.70 | .577 | 1.525<br>(21.5°) | 3.59<br>4.51 | 23,449<br>31,061 | .0417 |

(*Continued*)

TABLE Ia. (*Continued*)

| Sample Number | Sediment Type | Median Diameter Phi (mm) | Mean Diameter Phi | Phi Deviation Measure | Wet Density | Porosity | Sound Speed, km/sec (Temp. ° C.) | Sound Absorption, db/ft at c/s | | Acoustic Surface Area, $m^2$/g wet sed. |
|---|---|---|---|---|---|---|---|---|---|---|
| SD48a | fine sand | 2.22 (.215) | 2.25 | 0.37 | 1.96 | .422 | 1.722 (22.6°) | 3.04<br>2.73 | 23,362<br>26,263 | .0164 |
| SD48b | fine sand | 2.22 (.215) | 2.25 | 0.29 | 1.97 | .414 | 1.702 (22.7°) | 2.99<br>2.67 | 23,371<br>26,175 | .0165 |
| SD49a | medium sand | 1.82 (.284) | 1.78 | 0.64 | 1.99 | .402 | 1.742 (22.6°) | 3.93<br>2.66 | 23,573<br>26,515 | .0148 |
| SD49b | medium sand | 1.98 (.254) | 2.02 | 0.67 | 1.99 | .357 | 1.725 (22.2°) | 2.66 | 26,547 | .0164 |
| SD50a | very fine sand | 3.05 (.121) | 3.74 | 1.68 | 1.82 | .519 | 1.540 (22.8°) | 4.22<br>4.72 | 27,934<br>31,242 | .0334 |
| SD50b | fine sand | 2.68 (.156) | 3.15 | 1.39 | 1.80 | .526 | 1.550 (22.6°) | 6.27<br>7.28<br>5.89 | 23,943<br>27,153<br>31,194 | .0307 |
| SD51a | sandy coarse silt | 4.05 (.060) | 5.46 | 2.43 | 1.65 | .600 | 1.521 (20.7°) | 2.58<br>2.35<br>3.88 | 23,344<br>26,831<br>31,057 | .0385 |
| SD51b | sandy coarse silt | 3.96 (.064) | 5.29 | 2.17 | 1.69 | .561 | 1.525 (21.0°) | 2.47<br>3.21<br>5.24 | 23,350<br>27.002<br>31,045 | .0436 |
| SD52a | medium sand | 1.13 (.458) | 1.10 | 0.50 | 2.05 | .379 | 1.766 (22.6°) | 2.51 | 27,048 | .0082 |
| SD52b | medium sand | 1.27 (.415) | 1.05 | 0.57 | 2.05 | .376 | 1.756 (22.9°) | 2.44 | 27,032 | .0086 |
| SD53a | medium sand | 1.28 (.413) | 1.25 | 0.55 | 2.00 | .387 | 1.760 (22.5°) | 2.00 | 27,013 | .0096 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| SD53b | medium sand | 1.17<br>(.466) | 1.25 | 0.62 | 2.00 | .394 | 1.760<br>(22.6°) | 1.99<br>2.71 | 26,925<br>36,177 | .0083 |
| SD54a | fine sand | 2.62<br>(.163) | 2.48 | 0.38 | 1.88 | .482 | 1.770<br>(20.3°) | 4.5 | 31,192 | .0181 |
| SD54b | fine sand | 2.62<br>(.163) | 2.48 | 0.39 | 1.89 | .479 | 1.773<br>(20.7°) | 4.43 | 31,239 | .0181 |
| SD55a | fine sand | 2.72<br>(.152) | 2.71 | 0.35 | 1.96 | .426 | 1.680<br>(23.4°) | 3.05<br>4.01 | 25,853<br>29,603 | .0235 |
| SD55b | fine sand | 2.68<br>(.157) | 2.64 | 0.33 | 1.97 | .426 | 1.685<br>(22.0°) | 2.88<br>3.91 | 25,885<br>29,751 | .0223 |
| SD55c | fine sand | 2.68<br>(.157) | 2.64 | 0.32 | 1.95 | .432 | 1.686<br>(23.8°) | 2.65<br>2.86<br>3.88 | 23,219<br>25,885<br>29,719 | .0220 |
| SD55d | fine sand | 2.72<br>(.152) | 2.70 | 0.31 | 1.96 | .432 | 1.685<br>(22.2°) | 2.91<br>3.74 | 25,876<br>29,681 | .0229 |
| SD55e | fine sand | 2.74<br>(.150) | 2.67 | 0.32 | 1.98 | .427 | 1.693<br>(24.7°) | 3.59 | 26,090 | .0223 |
| SD55f | fine sand | 2.72<br>(.152) | 2.65 | 0.35 | 1.98 | .427 | 1.684<br>(24.3°) | 2.22<br>3.03<br>4.20 | 23,078<br>25,899<br>29,914 | .0227 |
| SD56a | fine sand | 2.02<br>(.247) | 2.76 | 1.49 | 1.95 | .426 | 1.685<br>(23.5°) | 5.0 | 29,678 | .0300 |
| SD56b | fine sand | 2.34<br>(.197) | 2.97 | 1.13 | 1.96 | .431 | 1.684<br>(19.8°) | 3.37<br>5.24 | 25,881<br>29,784 | .0296 |
| PC1 | fine sand | 2.12<br>(.230) | 2.11 | 0.39 | 1.93 | .440 | 1.735<br>(25.8°) | 6.31<br>4.90 | 26,650<br>31,044 | |
| PC2 | fine sand | 2.28<br>(.206) | 2.16 | 0.34 | 1.92 | .445 | 1.745<br>(25.25°) | 6.33 | 26,786 | |
| PC3 | fine sand | 2.20<br>(.218) | 2.19 | 0.30 | 1.95 | .424 | 1.725<br>(25.2°) | 7.64<br>8.00 | 26,540<br>30,799 | |

(*Continued*)

TABLE Ia. (*Concluded*)

| Sample Number | Sediment Type | Median Diameter Phi (mm) | Mean Diameter Phi | Phi Deviation Measure | Wet Density | Porosity | Sound Speed, km/sec (Temp. ° C.) | Sound Absorption, db/ft at c/s | | Acoustic Surface Area, $m^2$/g wet sed. |
|---|---|---|---|---|---|---|---|---|---|---|
| PC5a | fine sand | 2.25 (.210) | 2.19 | 0.44 | 1.98 | .397 | 1.715 (22.6°) | 2.83<br>2.83 | 26,364<br>30,448 | .0168 |
| PC5b | fine sand | 2.12 (.230) | 2.11 | 0.29 | 1.99 | .399 | 1.725 (23.8°) | 2.55<br>2.82 | 26,485<br>30,560 | .0158 |
| PC5c | fine sand | 2.12 (.230) | 2.10 | 0.35 | 1.996 | .397 | 1.731 (23.8°) | 2.54<br>2.79 | 26,549<br>30,525 | .0150 |

TABLE Ib. ACOUSTIC, GEOLOGIC, AND PHYSICAL PROPERTIES OF SEDIMENTS FROM INTERMEDIATE DEPTH
(Continental shelf, continental slope, continental borderland)

| Sample Number | Sediment Type | Median Diameter Phi (mm) | Mean Diameter Phi | Phi Deviation Measure | Wet Density g/$cm^3$ | Porosity | Sound Speed, km/s (Temp. ° C.) | Sound Absorption, db/ft at c/s | | Acoustic Surface Area, $m^2$/g wet sed. | Water Depth, meters | Location, N. Lat. W. Long. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CONTINENTAL SLOPE, ARCTIC OCEAN | | | | | | | | | | | | |
| AO8 | Clayey medium silt | 5.8 (.0173) | 6.83 | 2.85 | 1.67 | .604 | 1.551 (26.4°) | 2.193<br>1.668 | 23,263<br>31,030 | .0604 | 174 | 71°09′<br>150°24′ |
| AO7 | clayey fine silt | 6.4 (.0114) | 6.95 | 2.82 | 1.55 | .671 | 1.521 (26.8°) | 2.413<br>1.91 | 23,802<br>27,125 | .0560 | 232 | 71°08′<br>150°24′ |
| AO6 | clayey very fine silt | 7.4 (.0058) | 7.5 | 2.6 | 1.41 | .764 | 1.493 (26.8°) | 0.608<br>0.956 | 22,796<br>30,313 | .0404 | 439 | 71°10′<br>150°24′ |
| AO5 | silty coarse clay | 8.05 (.0038) | 8.35 | 2.4 | 1.32 | .812 | 1.491 (25.7°) | 0.435<br>0.401<br>1·315 | 20,500<br>22,768<br>30,225 | .0327 | 1,024 | 71°11′<br>149°54′ |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AO3 | silty coarse clay | 8.7 (.0025) | 7.10 | 2.7 | 1.305 | .826 | 1.486 (25.0°) | 0.201<br>0.560<br>0.918 | 20,395<br>22,766<br>30,300 | .0282 | 2,203 | 71°29′<br>149°39′ |
| AO2 | silty medium clay | 9.06 (.0019) | 9.75 | 2.1 | 1.306 | .834 | 1.486 (26.2°) | 0.649<br>0.582<br>0.644 | 20,496<br>22,714<br>30,185 | .0226 | 2,780 | 71°46′<br>148°41′ |
| | | | | | PIGEON POINT SHELF | | | | | | | |
| PP7 | coarse silt | 4.9 (.033) | 5.78 | 1.35 | 1.63 | .646 | 1.676 (26.2°) | 1.722<br>2.923<br>4,491 | 21,099<br>25,832<br>34,020 | .0364 | 77 | 37°07′<br>122°28′ |
| PP6 | coarse silt | 4.9 (.033) | 5.56 | 1.06 | 1.68 | .604 | 1.559 (27.4°) | 2.77 | 27,283 | .0475 | 88 | 37°05′<br>122°26′ |
| PP16 | medium silt | 5.0 (.031) | 5.22 | 0.61 | 1.73 | .550 | 1.526 (24.3°) | 6.71 | 31,053 | .0577 | 105 | 37°12′<br>122°30′ |
| PP2 | silty very fine sand | 3.9 (.067) | 3.96 | 0.59 | 1.88 | .464 | 1.756 (27.8°) | 4.51 | 30,775 | .0503 | 88 | 37°07′<br>122°33′ |
| | | | | | CONTINENTAL BORDERLAND OFF SOUTHERN CALIFORNIA | | | | | | | |
| CB1a | clayey very fine silt | 7.18 (.0069) | 7.27 | 2.25 | 1.39 | .796 | 1.518 (21.75°) | 1.772<br>2.45 | 23,169<br>30,881 | .0285 | 1,000 | for locations see Appendix |
| CB1b | clayey very fine silt | 7.20 (.0068) | 7.22 | 2.30 | 1.41 | .744 | 1.516 (22.1°) | 2.47 | 23,139 | .0344 | 1,000 | |
| CB2a | clayey very fine silt | 7.20 (.0068) | 7.36 | 2.40 | 1.45 | .730 | 1.504 (22.0°) | 0.625<br>0.846 | 22,916<br>30,518 | .0371 | 890 | |
| CB2b | clayey very fine silt | 7.10 (.0073) | 7.39 | 2.25 | 1.40 | .748 | 1.494 (21.4°) | 0.267<br>0.423<br>0.596 | 21,264<br>22,829<br>30,359 | | 890 | |
| CB3a | clayey fine silt | 6.98 (.0071) | 7.11 | 2.23 | 1.303 | .811 | 1.484 (22.4°) | 0.206<br>0.437<br>0.756 | 20,455<br>22,767<br>30,209 | .0270 | 1,142 | |
| CB3b | clayey very fine silt | 7.50 (.0055) | 8.15 | 2.65 | 1.335 | .794 | 1.488 (22.4°) | 0.190<br>0.318<br>0.732 | 20,437<br>22,750<br>30,225 | .0268 | 1,142 | |

(*Continued*)

TABLE Ib. (*Continued*)

| Sample Number | Sediment Type | Median Diameter Phi (mm) | Mean Diameter Phi | Phi Deviation Measure | Wet Density g/cm³ | Porosity | Sound Speed, km/s (Temp. ° C) | Sound Absorption, db/ft at c/s | | Acoustic Surface Area, m²/g wet sed. | Water Depth, meters | Location, N. Lat. W. Long. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CB3c | clayey very fine silt | 7.24 (.0066) | 7.73 | 2.35 | 1.346 | .792 | 1.489 (20.5°) | 0.296<br>0.514<br>0.687 | 20,391<br>22,690<br>30,206 | .0343 | 1,142 | |
| CB4a | clayey very fine silt | 7.36 (.0061) | 7.91 | 2.29 | 1.292 | .856 | 1.489 (22.0°) | 0.441<br>0.458<br>0.810 | 20,425<br>22,757<br>30,233 | .0244 | 1,173 | |
| CB4b | clayey very fine silt | 7.20 (.0068) | 7.75 | 2.31 | 1.355 | .796 | 1.498 (21.4°) | 0.217<br>0.378<br>0.544 | 20,414<br>22,753<br>30,249 | ·0404 | 1,173 | |
| CB4c | clayey very fine silt | 7.20 (.0068) | 7.83 | 2.25 | 1.352 | .785 | 1.499 (22.5°) | 0.854<br>1.309 | 22,912<br>30,509 | .0436 | 1,173 | |
| CB5a | clayey fine silt | 6.90 (.0084) | 7.36 | 2.05 | 1.289 | .745 | 1.500 (22.8°) | 0.283<br>0.554<br>1.148 | 20,483<br>22,802<br>30,260 | .0554 | 1,198 | |
| CB5b | clayey very fine silt | 7.10 (.0073) | 7.66 | 2.25 | 1.334 | .799 | 1.492 (23.2°) | 0.295<br>0.591<br>0.914 | 20,504<br>22,847<br>30,334 | .0399 | 1,198 | |
| CB5c | clayey very fine silt | 7.26 (.0065) | 7.81 | 1.95 | 1.348 | .782 | 1.495 (23.2°) | 0.434<br>0.445<br>0.634 | 20,658<br>22,801<br>30,337 | .0429 | 1,198 | |
| CB6a | clayey fine silt | 6.96 (.008) | 7.49 | 2.20 | 1.301 | .814 | 1.517 (22.6°) | 1.01<br>1.90<br>1.03 | 21,256<br>23,122<br>30,712 | .0375 | 1,218 | |
| CB6b | clayey fine silt | 7.00 (.0078) | 7.68 | 2.36 | 1.345 | .789 | 1.493 (23.7°) | 0.323<br>0.412<br>0.630 | 20,496<br>22,842<br>30,278 | .0414 | 1,218 | |
| CB6c | clayey medium silt | 7.45 (.0057) | 7.95 | 2.45 | 1.370 | .778 | 1.525 (23.0°) | 1.009<br>1.200 | 23,428<br>30,746 | .0416 | 1,218 | |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| CB7 | coarse silt | 4.58 (.042) | 5.34 | 1.20 | 1.729 | .516 | 1.534 (23.8°) | 2.543<br>3.937 | 23,551<br>31,218 | .0628 | 132 |
| CB8a | coarse silt | 4·90 (.0425) | 6.38 | 2.02 | 1.578 | .663 | 1.510 (23.9°) | 1.427<br>1.168 | 23,269<br>30,752 | .0529 | 183 |
| CB8b | clayey medium silt | 5.22 (.0265) | 6.66 | 2.30 | 1.590 | .656 | 1.506 (23.9°) | 0.762<br>1.773 | 23,083<br>30,663 | .0517 | 183 |
| CB8c | clayey medium silt | 5.60 (.0206) | 7.17 | 2.52 | 1.594 | .651 | 1.506 (24.5°) | 0.569<br>1.364 | 23,068<br>30,655 | .0539 | 183 |
| CB9a | coarse silt | 4.70 (.039) | 5.64 | 1.45 | 1.597 | .634 | 1.545 (23.9°) | 2.49<br>3.89 | 23,861<br>31.203 | .0420 | 179 |
| CB9b | clayey medium silt | 5.40 (.024) | 6.80 | 2.28 | 1.590 | .659 | 1.512 (23.2°) | 0.902<br>0.836<br>1.590 | 20,818<br>23,324<br>30,603 | .0409 | 179 |
| CB10 | clayey coarse silt | 4.86 (.034) | 6.69 | 2.40 | 1.645 | .622 | 1.518 (23.6°) | 1.222<br>2.301 | 23,329<br>30,957 | .0503 | 205 |
| CB11a | coarse silt | 4.38 (.048) | 4.33 | 0.45 | 1.827 | .522 | 1.532 (24.1°) | 5.718 | 31,226 | .0550 | 84 |
| CB11b | sandy coarse silt | 4.28 (.051) | 4.34 | 0.66 | 1.838 | .512 | 1.556 (24.0°) | 5.203<br>5.364 | 23,958<br>31,240 | .0554 | 84 |
| CB12 | sandy coarse silt | 4.34 (.050) | 4.35 | 0.50 | 1.816 | .524 | 1.556 (24.0°) | 5.40<br>5.53 | 24,200<br>31,250 | .0548 | 84 |
| CB13a | sandy coarse silt | 4.27 (.052) | 2.77 | 2.65 | 1.904 | .458 | 1.63 (25.2°) | 5.549 | 31,281 | .0511 | 99 |
| CB13b | sandy coarse silt | 4.44 (.046) | 2.89 | 2.60 | 1.900 | .463 | 1.60 (25.4°) | 4.975 | 31,264 | .0506 | 99 |
| CB13c | sandy coarse silt | 4.44 (.046) | 3.27 | 2.72 | 1.882 | .481 | 1.60 (25.0°) | 6.01<br>5.74 | 24,653<br>31,175 | .0497 | 99 |
| CB14 | sandy coarse silt | 4.33 (.050) | 4.14 | 0.86 | 1.895 | .487 | 1.586 (24.6°) | 4.778<br>5.922 | 24,376<br>31,182 | .0536 | 99 |

(*Continued*)

TABLE Ib. (*Concluded*)

| Sample Number | Sediment Type | Median Diameter Phi (mm) | Mean Diameter Phi | Phi Deviation Measure | Wet Density g/cm³ | Porosity | Sound Speed, km/s (Temp. ° C) | Sound Absorption, db/ft at c/s | | Acoustic Surface Area, m²/g wet sed. | Water Depth, meters | Location, N. Lat. W. Long. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CB15 | coarse silt | 4.73 (.038) | 5.57 | 1.66 | 1.747 | .570 | 1.560 (24.7°) | 1.786<br>1.786 | 21,440<br>23,689 | .0558 | 137 | |
| CB16a | sandy coarse silt | 4.26 (.052) | 3.68 | 1.00 | 1.800 | .554 | 1.550 (25.4°) | 4.910<br>5.737 | 23,848<br>31,291 | .0417 | 137 | |
| CB16b | sandy coarse silt | 4.60 (.041) | 5.62 | 2.60 | 1.779 | .540 | 1.545 (25.1°) | 4.711<br>5.324 | 23,826<br>31,181 | .0488 | 137 | |

TABLE Ic. ACOUSTIC, GEOLOGIC, AND PHYSICAL PROPERTIES OF DEEP-SEA SEDIMENTS

| Sample Number | Sediment Type | Median Diameter Phi (mm) | Mean Diameter Phi | Phi Deviation Measure | Wet Density | Porosity | Sound Speed, km/s (Temp. ° C.) | Sound Absorption db/ft at c/s | | Acoustic Surface Area, m²/g wet sed. | Water Depth, meters | Location, N. Lat. W. Long. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PO1 | red coarse clay | 8.96 (.002) | 9.06 | 0.93 | 1.446 | .689 | 1.596 ± .02 (18.7°) | 0.52 | 25.4 kc/s | .0333 | 5,706 | 27°32′ 154°06′ |
| PO2 | red very fine silt | 7.16 (.007) | 7.45 | 2.9 | 1.44 | .710 | 1.60 ± .02 (20.6°) | 0.70<br>1.37 | 26.3 kc/s<br>30.5 kc/s | .0478 | 4,122 | 21°32.8′ 157°08.8′ |
| PO3 | red coarse clay | 8.38 (.003) | 9.01 | 1.9 | 1.50 | .743 | 1.52 ± .02 (19.7°) | 1.29<br>1.99 | 29.8 kc/s<br>26.2 kc/s | .0287 | 4,254 | 23°21.5′ 156°28.7′ |
| PO4 | red coarse clay | 8.96 (.002) | — | — | 1.30 | .804 | 1.52 ± .02 (24.7°) | 0.31 | 35,660 | | 4,208 | 31°51.9′ 121°30.8′ |
| PO5 | green very fine silt | 7.6 (.005) | 8.03 | 2.45 | 1.43 | — | 1.51 ± .02 | 0.8 | 24,014 | | 3,620 | 35°52.5′ 123°16′ |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PO6b | silty medium clay | 9.04 (.0019) | 9.1 | 2.64 | 1.310 | .823 | 1.540 (21.2°) | 0.544<br>1.28<br>1.42 | 20,583<br>23,347<br>31,470 | .0233 | 3,750 | 32°27′<br>120°41′ |
| PO6d | silty coarse clay | 8.94 (.002) | 9.0 | 2.70 | 1.319 | .806 | 1.493 (23.7°) | 0.189<br>0.478<br>0.500 | 20,481<br>22,810<br>30,325 | .0265 | 3,750 | 32°27′<br>120°41′ |
| PO7 | calcareous silty coarse clay | 8.05 (.0038) | 7.42 | 2.90 | 1.485 | .694 | 1.518 (23.6°) | 1.057<br>1.245<br>1.907 | 21,515<br>23,690<br>30,640 | .0392 | 3,720 | 13°29′S*<br>108°33.5′ |
| PO8 | calcareous clayey very fine silt | 7.60 (.0052) | 7.21 | 2.65 | 1.369 | .783 | 1.493 (23.4°) | 0.958<br>1.103<br>1.265 | 20,388<br>22,764<br>30,269 | .0328 | 4,610 | 03°42′S*<br>114°09′ |

TABLE Id. ACOUSTIC, GEOLOGIC, AND PHYSICAL PROPERTIES OF MISCELLANEOUS SEDIMENTS

| Sample Number | Sediment Type | Median Diameter Phi (mm) | Mean Diameter Phi | Phi Deviation Measure | Wet Density g/cm³ | Porosity | Sound Speed, km/s (Temp. ° C.) | Sound Absorption, db/ft at c/s | | Acoustic Surface Area, m²/g wet sed. | Water Depth, meters | Location, N. Lat. W. Long. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SP1 | fine sand | — | — | — | 2.065 | .363 | 1.744 (20°) | 1.939<br>3.194 | 26,381<br>36,151 | .0408 | — | — |
| All particles between 0.25 and 0.125 mm; distilled water; from disaggregated St. Peter sandstone | | | | | | | | | | | | |
| SP2 | sandy coarse silt | 4.56 (.046) | 4.89 | 1.25 | 1.79 | .623 | 1.540 (20°) | 2.280<br>4.777 | 23,684<br>31,267 | .0487 | 82 | 32°41′27″<br>117°18′30″ |
| SP3 | calcareous sandy coarse silt | 4.75 (.037) | 5.87 | 2.95 | 1.57 | .666 | 1.483 (20°) | 4.996 | 30,240 | .0411 | 1,700 | 17°07′<br>117°17′ |
| SP4 | red medium clay | 9.40 (.015) | 9.40 | 1.53 | 1.338 | .809 | 1.474 (20°) | 0.149 | 28,413 | .0215 | 5,220 | 37°15′<br>143°07′ |

EDITOR'S NOTE: Part II of this paper will appear in the next issue of GEOPHYSICS.

* South Latitude.

in the Arctic Ocean. These are designated by the prefix AO. Locations are given in Table I.

A group of samples were taken by core, dredge, and snapper from the continental shelf off Pigeon Point, California. These are designated by the prefix PP. A discussion of the sediments of the Pigeon Point shelf and their geologic setting is given by Moore and Shumway (1959).

Additional sediments from intermediate depth were obtained from the continental borderland area off San Diego, where a varied topography provides a variety of sediments ranging from sands to clays. These are designated by the prefix CB.

*Deep-sea sediments*

All of these samples were obtained from cores collected in the eastern Pacific Ocean, and are identified by the prefix PO. Two of the cores were from the southeast Pacific Ocean, the remainder being from the northeast Pacific Ocean.

## THEORIES OF SOUND PROPAGATION IN COMPOSITE MEDIA

The gamut of sedimentary materials found in nature has, at one extreme, high-porosity suspensions of colloidal clay particles and, at the other, low-porosity porous solids. Natural unconsolidated sediments in the sea range from suspensions of particles with diameters of the order of one micron to tightly packed aggregates of sand grains and granules with diameters of the order of 1,000 microns. In the development of sound propagation theory, models representing these extreme cases generally have been used. The case of the general unconsolidated sediment, in which are present both small suspended particles and relatively large particles in various degrees of mutual contact, has been neglected, due to its complexity and to the fact that in science and industry the extreme cases find broader application than does the general case.

The acoustic behavior of natural unconsolidated water-saturated sediments is essentially that of a suspension of particles in a fluid, but a small rigidity is present that cannot be neglected. Theories for suspensions and for granular aggregates are more pertinent for these sediments than are theories for porous solids; however, certain aspects of porous solid theory are applicable. A brief review of some theoretical developments which most directly relate to the present studies is given below, to provide a background for viewing the experimental results.

A. B. Wood (1930, p. 326–329) noted that in a dispersion of one or more fluids in another the bulk adiabatic compressibility equals the sum of the compressibilities of the individual components multiplied by their proportional volumes in the total volume. A corresponding relation holds for bulk density. A simple expression then, can be written for sound velocity, $C_{ws}$, in the mixture in terms of the properties of the components:

$$C_{ws}^2 = \frac{1}{[\Sigma f_{si}\beta_{ei}][\Sigma f_{si}\rho_{si}]}, \tag{1}$$

where $f_{si}$ are the volume fractions for the $i$ components, $\beta_{si}$ the compressibilities of the $i$ components, and $\rho_{si}$ the densities of the $i$ components. Urick (1947, p. 983–987) applied this equation to the case of suspensions or emulsions under the assumption that the suspended particles are infinitesimally small compared with the wave length of sound, hence scattering effects can be neglected.

Urick and Ament (1949) suggested an improvement to the homogenous assumption theory equation (1) with the development of a first order theory, which, in allowing for first order scattering effects, gives a complex propagation constant whose real part yields a velocity that reduces to the homogenous case for very small particles. Ament (1953) carried the work further by determining effective dynamic densities for gross mixtures in the form of either a porous solid or a suspension.

In the case of the somewhat rigid structure of solid grains with fluid-filled channels, compressional waves and shear waves are transmitted by the frame, and compressional waves also are transmitted by the fluid. If coupling between the two phases is good, as in a water-filled sediment, compressional velocity, $C_{ws}$, may be related to the bulk properties of the sediment by the well-known equation

$$C_{ws}^2 = \frac{K_{ws} + (4/3)\mu_{ws}}{\rho_{ws}}, \tag{2}$$

where $\mu_{ws}$ is the rigidity modulus of the aggregate, $\rho_{ws}$ is the bulk density and equal to $f_w\rho_w + \Sigma f_{si}\rho_{si}$, and $K_{ws}$ is the bulk modulus of the aggregate. For perfect coupling, Gassmann (1951a) showed that the aggregate bulk modulus is a function of the fluid bulk modulus, the particle bulk modulus, and the frame bulk modulus.

Laughton (1957) investigated the justification of using the relation

$$1/K_{ws} = f_w\beta_w + \Sigma(f_{si}/K_{si}). \tag{3}$$

He introduced a structure bulk modulus, $K_c$, so that for a two-component system the aggregate modulus is

$$K_{ws} = \frac{K_s K_w(1 + f_w/f_s)}{K_w + (f_w/f_s)K_s} + K_c. \tag{4}$$

Through static decompression measurements Laughton obtained values for $K_c$. Then by using equation (4) together with equation (2) he showed that for the two fine-grained deep-sea sediments he studied, at compacting pressures below about 490 bars, rigidity is negligible.

For the general sediment the most useful equation for predicting sound speed is the following,

$$C_{ws}^2 = \frac{K_{ws} + 4\mu_{ws}/3}{\Sigma f_{si}\rho_{si} + f_w\rho_w}, \tag{5}$$

where $K_{ws}$ is determined as in equation (3).

A number of other theoretical studies with regard to granular materials and porous solids have been made and it will suffice here to mention some briefly. Gassmann (1951b) dealt with spheres in hexagonal close packing and showed that compressional velocity should increase in proportion to the sixth root of the depth of burial. This same result was obtained earlier by Iida (1938, 1939) and by Takahashi and Sato (1949). The theory was extended by White and Sengbush (1953). Brandt (1954, 1955) developed theoretical expressions to explain the influence of pressure, porosity, and liquid saturation on sound speed in a porous granular medium, using as a model an aggregate of randomly stacked spherical particles of four different sizes. Sato (1952) gave expressions for compressional wave propagation in media with small holes and in media containing small obstacles, as an extension of the theory of Mackenzie (1950) for a solid containing spherical holes. Kerner (1956) determined theoretically the gross elastic moduli of a composite medium in terms of the properties of its components.

Biot's general treatment of elastic wave propagation in porous solids (1956a) at low frequencies (where Poiseuille flow holds) predicts a rotational wave whose phase velocity increases slightly with frequency and whose absorption coefficient is proportional to the square of the frequency. It predicts a dilatational wave which has practically a negligible dependence of phase velocity on frequency and an absorption coefficient proportional to the *square of the frequency.* In a second paper Biot (1956b) treats the frequency range high enough that Poiseuille flow does not hold but not so high that wave length is smaller than pore size. A structure factor is introduced to account for pore shape, and it is shown that this is not a very significant parameter. The dilatational wave is found to have a velocity which increases slightly with frequency, and an absorption coefficient proportional to the *square root of frequency.* The rotational wave velocity increases somewhat with frequency, and the absorption coefficient is proportional to the square root of frequency.

Relatively little work has been done on the absorption of sound in aqueous suspensions and in water-filled granular aggregates. Sewell (1910) considered the case of small rigid particles which are immobile in the sound field—a condition satisfied for water droplets in air at audio frequencies, but not for aqueous suspensions. Lamb (1945, p. 657–661) condensed Sewell's treatment and extended it to include the case of rigid incompressible particles free to move in the sound field. Urick (1948) discussed Lamb's theory and rewrote his result in the form of an intensity absorption coefficient for a unit volume, $\alpha$, defined by $I = I_0 \exp(-\alpha x)$ as:

$$\alpha = \frac{4}{3}\pi a^2 n\left[\frac{1}{6}k^4a^3 + k(\sigma - 1)^2\frac{s}{s^2 + (\sigma + \tau)^2}\right], \tag{6}$$

where $a$ is the particle radius, $n$ is the number of particles per unit volume, $k$

is the wave number and equal to $2\pi/\lambda$, $\lambda$ is the wave length, $\sigma$ is the ratio of particle density $\rho_s$ to fluid density $\rho_w$, i.e. $\sigma = \rho_s/\rho_w$, and where the following relations hold when $\omega$ is the angular frequency and $\mu$ is the kinematic viscosity of the fluid:

$$a = (9/4a)(1 + 1/\beta a); \qquad \beta = (\omega/2\mu)^{1/2}; \qquad 1/2 + 9/4\beta a.$$

The first term on the right side of equation (6) is the scattering loss by small rigid spherical particles free to move in the sound field; the second term is a frictional loss due to the fluid viscosity. It is the second term which accounts for most of the observed absorption in aqueous suspensions.

## SOUND SPEED AND ABSORPTION MEASUREMENTS

Sound speed and absorption measurements by the resonance method are given in Table I together with other physical data. All measurements were made at "room temperature," which was anywhere between 19°C. and 28°C., hence the temperatures at which the measurements were made are recorded along with the sound speed values. Inasmuch as absorption is a frequency-dependent process, the resonant frequency is given for each value. For most samples more than one resonant mode was detected and absorption data taken.

GEOPHYSICS, VOL. XXV, NO. 2 (APRIL, 1960), PP. 468–482, 13 FIGS.

# TWO-DIMENSIONAL MODELING AND ITS APPLICATION TO SEISMIC PROBLEMS*

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## ABSTRACT

Laboratory seismograms of a fault model demonstrate the mechanism for diffraction and clearly show the difference in amplitude decay and moveout between a reflection and a diffraction. The inverted order and the deflection to the side of reflected energy from a curved reflector with a buried focus is demonstrated. A comparison is made of seismograms from a simple fault model and from one combining a fault with curved reflectors leading to it. The curved surfaces increase the overlap of the reflected events and mask the fault. Modeling techniques, involving the control of the reflection coefficient between layers by thickness variations and the control of the propagation velocity through a layer by combining two or more materials into a laminated sheet, are demonstrated.

## INTRODUCTION

In recent years the petroleum geophysicist has become more concerned with the basic fundamentals of wave propagation in solid media because of his need for more information from field seismograms. Since the turn of the century, numerous workers have made theoretical studies of wave motion in solids; however, because of the complexity of the problem, only those cases with the simplest of geometries have been solved successfully. Consequently, there is a wide gap between the problems of interest to the seismic field party and those which can be solved by the theoretical geophysicist. A laboratory seismic model can bridge this gap. The intent of this paper is to demonstrate the application of two-dimensional seismic modeling to field problems.

Seismic modeling has been the subject of a large number of papers in the past ten years. A partial list of these papers is included in the references. As can be noted from the titles, a wide range of problems can be solved by model techniques.

Seismic models can be classified into three groups depending on the number of dimensions employed. A one-dimensional model may be constructed in different forms such as the sound tube described by Woods (1956), or the plastic rod as used by Berryman et al. (1958), or the metal rod with cross-sectional area changes in scaled correspondence to velocity changes of a velocity log as described in the author's U. S. Patent No. 2,834,422. The one-dimensional model is ideal for the studying of the relationships of many reflections and the problem associated with ghosts and multiples. This type of model is concerned only with normal incidence of acoustic waves, and assumes that each layer is flat and horizontal.

Oliver et al. (1954), introduced the two-dimensional model. Thin sheets of

* Manuscript received by the Editor September 1, 1959.

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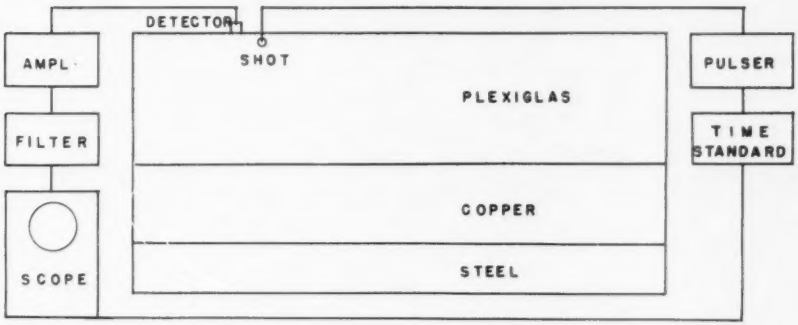


FIG. 1. A schematic diagram of a typical seismic model.

elastic materials cut into the form of a disc or cut into strips and bonded together to form a layered cross-section are examples of this type. Reflection, refraction, and surface wave problems can be solved with the two-dimensional seismic model. Both the two- and three-dimensional models are well suited for studying configurations where geometrical effects are of predominant interest. In areas where the stratigraphy does not change appreciably in the horizontal direction perpendicular to the geophone spread, the two-dimensional model can be used without any serious loss of generality.

Three-dimensional models as described by Howes et al. (1953) and by Evans et al. (1954), are representative of the third type of seismic model. Only a limited number of materials are sufficiently homogeneous to be used as components for these models. In addition, the fabrication of all but the most simple geometries is more difficult than for the other two types of models. Consequently, the three-dimensional model is best suited to those problems concerned more with the basic processes of reflection, refraction, and diffraction than with geometrical effects or where stratigraphic changes perpendicular to the spread cannot be neglected.

## TWO-DIMENSIONAL MODEL

The essential components of any seismic model are (1) one or more elastic materials arranged in a desired geometry, (2) a source of acoustic pulses, and (3) a means for detecting the resulting motions. The means by which these essentials are realized differ only slightly from one model system to another. The model system developed by the Socony Mobil Field Research Laboratory is shown in schematic form in Figure 1.

The materials used for the models are $\frac{1}{16}$ in thick sheets of plexiglas, copper, aluminum, and steel. These sheets are cut to the desired geometry and bonded together with epoxy resin. The source and receiver units are made of barium titanate. The shape and size of these units are chosen to produce an elas-

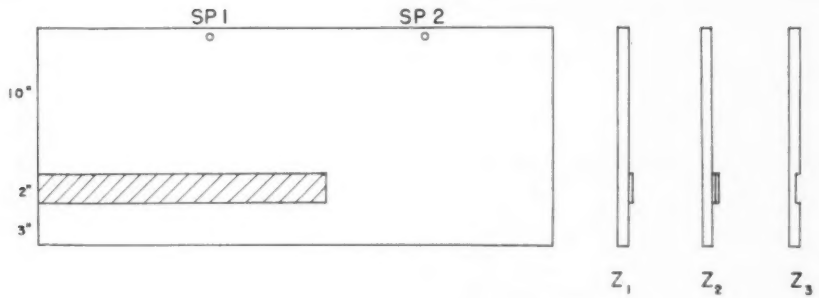


FIG. 2. A schematic drawing of model with variations in thickness.

tic pulse of reasonably short duration and with a peak frequency in the vicinity of 200 kc/sec. The pulser unit consists of a thyratron and pulse forming network which yields an electric pulse consisting of a single peak having a width of approximately five microsec and with an amplitude ranging from 100 to 1,000 volts. The received signal is amplified by a broad band (five cps to two Mcs) amplifier and filtered by an SKL electrical filter. This signal is presented to a Tektronix 535 oscilloscope and photographed with a Polaroid camera. A Tektronix Time-Mark Generator is used to Z-axis modulate the scope beam at 10 or 100 microsec intervals. The source is actuated every 20 millisec and the detector is moved from point to point to give any spread configuration desired. The picture is then enlarged and timing lines are superimposed to obtain a model seismogram resembling a field record.

## MODELING TECHNIQUES

As mentioned above, models consisting of more than one layer are usually fabricated by bonding together materials of different acoustic properties. However, there are only a dozen or so materials readily available in sheet form for models. Consequently, the reflection coefficient at the boundaries of a layer and the propagation velocity through the layer are restricted by the materials available. These restrictions, however, can be eliminated.

### *Reflection Coefficient*

The reflection coefficient at the junction of two materials is determined by the contrast in the acoustic impedance of the materials. The acoustic impedance for the plate is the product of the acoustic velocity, the density, and the thickness; consequently, a change in any one of these parameters will introduce a reflection in an otherwise uniform plate. A multi-layered model with *prescribed* reflection coefficients can thus be fabricated from a single sheet of material by either increasing or decreasing the thickness of the sheet at prescribed depths.

The influence of thickness change on the amplitude and polarity of a reflec-

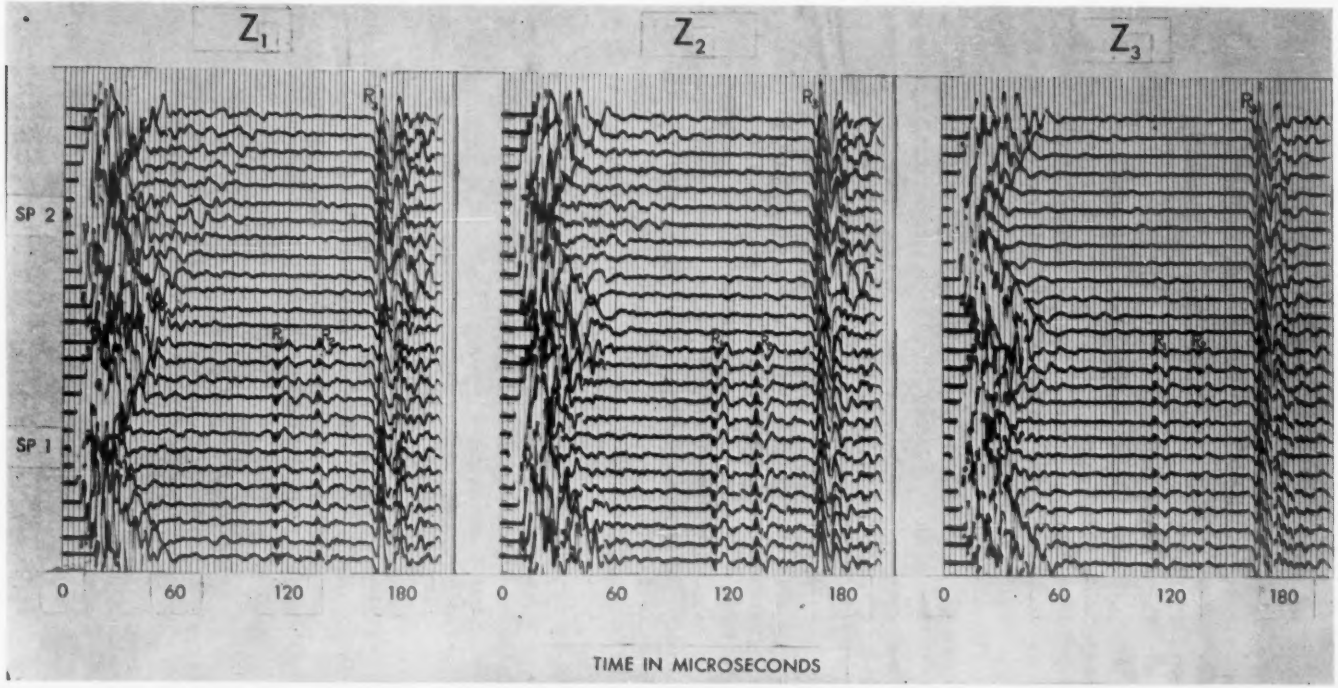


FIG. 3. Model records showing influence of thickness on the polarity and amplitude of a reflection.

tion is shown in Figures 2 and 3. The base material of this model (Figure 2) is an aluminum sheet of .063 inch thickness. Model $Z_1$ has an additional strip of .016 inch aluminum bonded to it, model $Z_2$ has two such strips, and model $Z_3$ has a recess of .013 inch depth. The records from these three models are presented in Figure 3. Each of these records was shot under identical conditions with conventional split spreads about SP 1 and SP 2. The largest reflection, $R_3$, is from the base of the model while reflections $R_1$ and $R_2$ are from the top and bottom of the layer of thickness change.

The observed polarity and amplitude of each of these reflections agree with those predicted. Reflection $R_1$ and $R_2$ are of opposite polarity for each of the models. The amplitudes of $R_1$ and $R_2$ for model $Z_2$ are approximately twice those for $Z_1$ and $Z_3$. Also the polarity of the first two reflections of model $Z_3$ are opposite to those of model $Z_1$ and $Z_2$ due to the decrease instead of the increase in thickness.

*Composite Velocity*

The restriction of only those propagation velocity values as are possessed by the few materials readily available for modeling is eliminated by combining two or more materials into a composite sheet. This composite sheet is made by bonding face to face thin sheets of different materials. The materials chosen and their respective thicknesses allow a composite velocity ranging continuously between the extremes of the materials used. For wave lengths long compared to the overall thickness of the composite sheet, the velocity can be expressed as

$$\overline{C}^2 = \frac{\alpha_1\rho_1 C_1^2 + \alpha_2\rho_2 C_2^2 + \cdots \alpha_n\rho_n C_n^2}{\alpha_1\rho_1 + \alpha_2\rho_2 + \cdots \alpha_n\rho_n}, \tag{1}$$

where

$\alpha_n$ is the fraction of material $n$
$\rho_n$ is the density of material $n$
$C_n$ is the acoustic velocity of material $n$.

A number of composite strips measuring 3×12 in were made of various pairs of materials. The transit time for a number of transversals across the three-inch dimension of the strips was accurately measured with the aid of a Rutherford Time Delay Generator. The composite velocity was determined by dividing this transit time into twice the width of the strip. A comparison of the measured and the calculated composite velocities in inches per microsecond is shown in

TABLE I

| Material 1 | Material 2 | $\alpha_1$ | $\alpha_2$ | $\overline{C}_{\text{calc.}}$ | $\overline{C}_{\text{meas.}}$ |
|---|---|---|---|---|---|
| Aluminum (0.213) | Epoxy (0.077) | 0.24 | 0.76 | 0.151 | 0.149 |
| Aluminum (0.213) | Plexiglas (0.090) | 0.20 | 0.80 | 0.147 | 0.148 |
| Steel (0.210) | Solder (0.084) | 0.41 | 0.49 | 0.146 | 0.146 |

Table I. The plate velocity for the individual component materials is given in the parenthesis in units of inches per microsecond.

A larger test section was made from a sheet of steel 16×36 in with a recessed section 4×26 in and with a depth of 0.040 in. Normal model records were taken over the model before and after a layer of solder was added. A sketch of the model is shown in Figure 4. The side-view drawings show model $Z_4$ to be steel only and model $Z_6$ to have a 0.017 in layer of solder added. Reflections from the top and bottom of the 4-in strip, denoted as $R_1$ and $R_2$, and the bottom reflection $R_3$, can be carried across the records of Figure 5. The propagation velocity of the 4-in strip can be determined from the time difference of events $R_1$ and $R_2$. This time

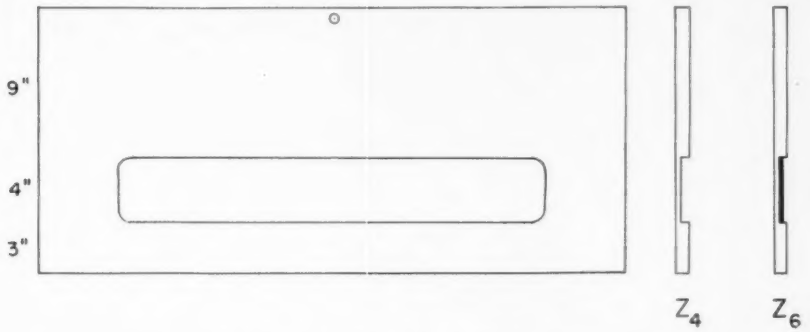


FIG. 4. Model composed of steel and solder to show change in velocity for composite section.

interval for model $Z_4$ yields a velocity of 0.205 in/microsec which is within three percent of the more accurately measured value of steel. The $R_1$ to $R_2$ time interval for $Z_6$ is seen to be appreciably longer and gives a velocity of 0.150 in/microsec. This value is approximately eight percent lower than that calculated for the composite layer of steel and solder. Some machining difficulties were encountered because of the flimsiness of the steel sheet. Consequently, the thickness of the steel and of the solder varied as much as 0.002 in. This uncertainty of the thickness could account for the discrepancy in the measured composite velocity.

## APPLICATIONS OF SEISMIC MODELING

Sections containing faults and folds are of paramount interest to the explorationist; however, the seismograms from these regions are complex and at times tend to defy detailed interpretation. Consequently, simple faults and geometries containing curved surfaces are fruitful subjects for seismic modeling.

### *Fault Model*

A fault model consisting of a sheet of aluminum and copper is shown in Figure 6. In addition to the reflections $R_H$, $R_L$, and $R_b$ from the interfaces labeled $H$,

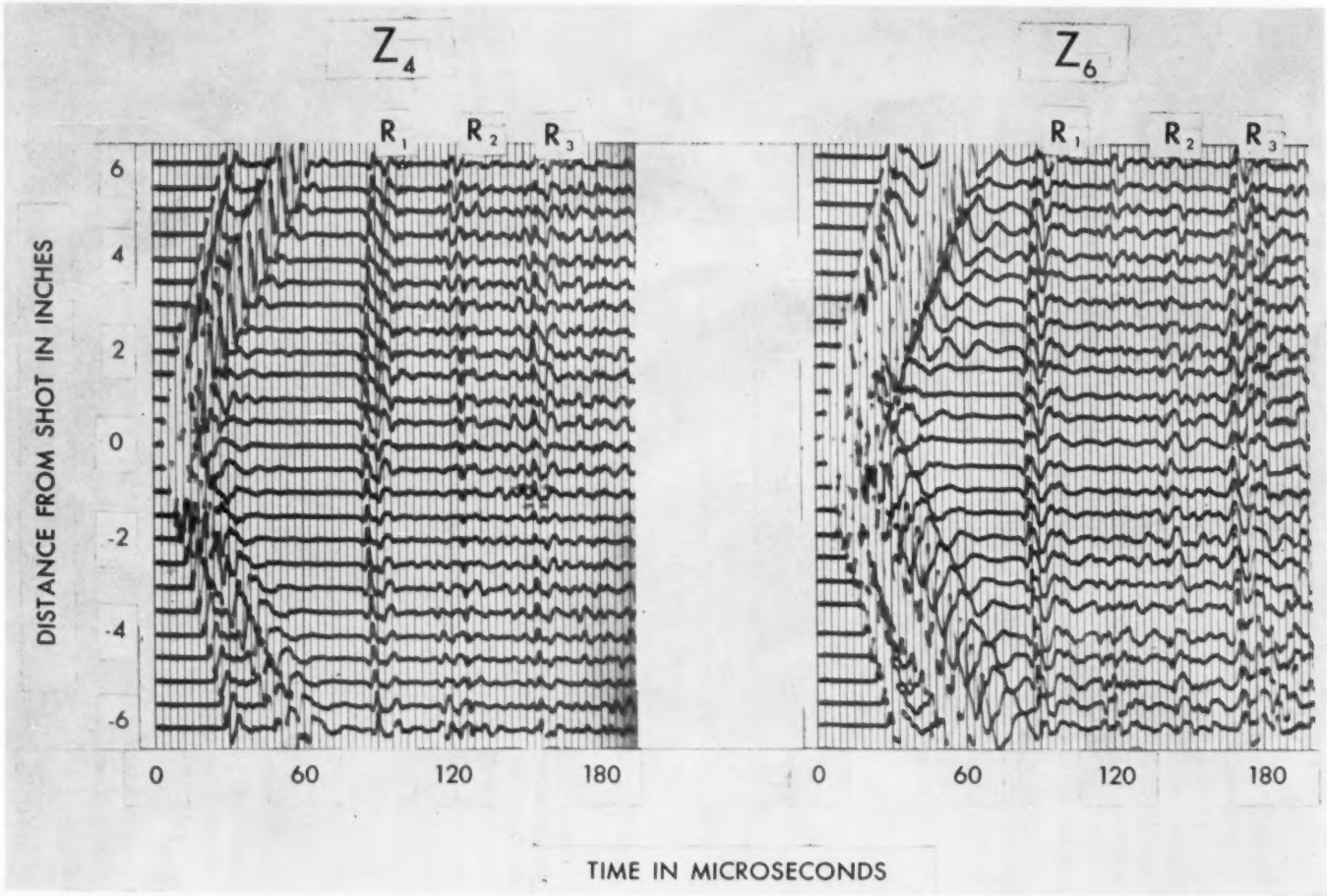


FIG. 5. Model records showing increase in time interval between reflections $R_1$ and $R_2$ when solder is added.

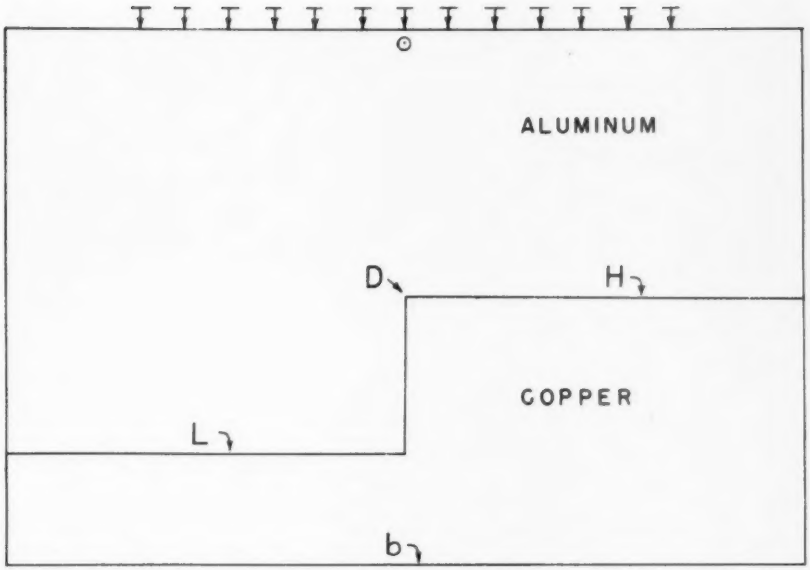


FIG. 6. A simple fault model.

$L$, and $b$, respectively, four diffraction events, two converted events, and two multiple events can be picked on the record of Figure 7.

The diffractions can be identified by both the increase in moveout and the amplitude decay with distance away from the fault. The phenomena of diffraction can be understood by employing the concepts of Huygen's principle and of limitation of a wave front. When a wave front is limited by the termination of a reflector, such as at a fault or at a wedgeout, a diffraction will occur. Hence, it is not too surprising to observe four different diffractions from the top edge, labeled $D$, of the fault plane. The diffraction $D_1$ is due to the abrupt termination of reflector $H$. The event $D_1+$ is generated by the limitation of the reflected wave front from interface $L$. The reflection from the bottom of the model separates into two events because of the difference in transit time on the two sides of the fault. Each of these wave fronts is limited by the top edge of the fault plane and thus causes the diffractions labeled $D_1{}^{++}$.

*Curved Surface Model*

A reflecting interface at sufficient depth and with sufficient curvature to develop a buried focus as discussed by Dix (1952) is modeled in Figure 8. The general characteristic of a buried focus is that energy reaching the surface is deflected to the side and the order in which energy is received at the surface is in-

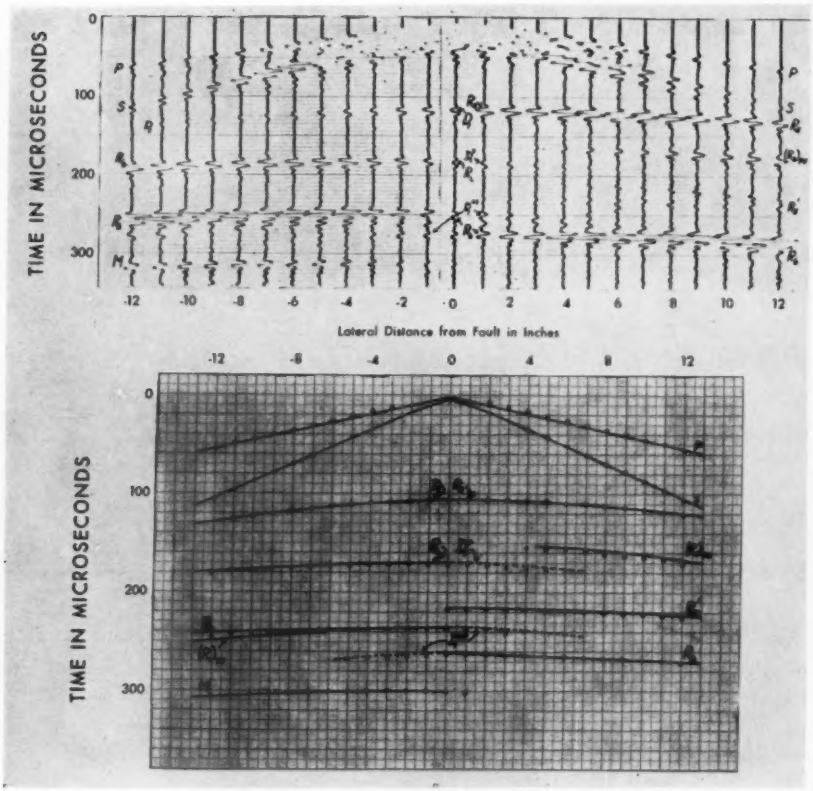


FIG. 7. Model record and time section of a simple fault.

verted from that arriving at the interface. These characteristics can be observed by following event $R_1$ across the record of SP 1 to the middle of SP3. At this point the curved surface reflection $R_{C_1}$ is deflected back toward the left. The further toward the right is the reflecting point, the more to the left is the energy received at the surface. This inversion continues to the inflection point between curves $C_1$ and $C_2$. If the reflection $R_{C_2}$ had greater amplitude, it would tie to $R_{C_1}$ at the extreme left of the record. This event continues across the SP 5 spread. The small event $D_1$ is a diffraction from the region where the reflecting interface changes from a flat surface to a concave surface.

*Complex Fault Model*

Model records from a simple fault and from curved reflectors have been presented. These records are relatively simple and from them one can reconstruct

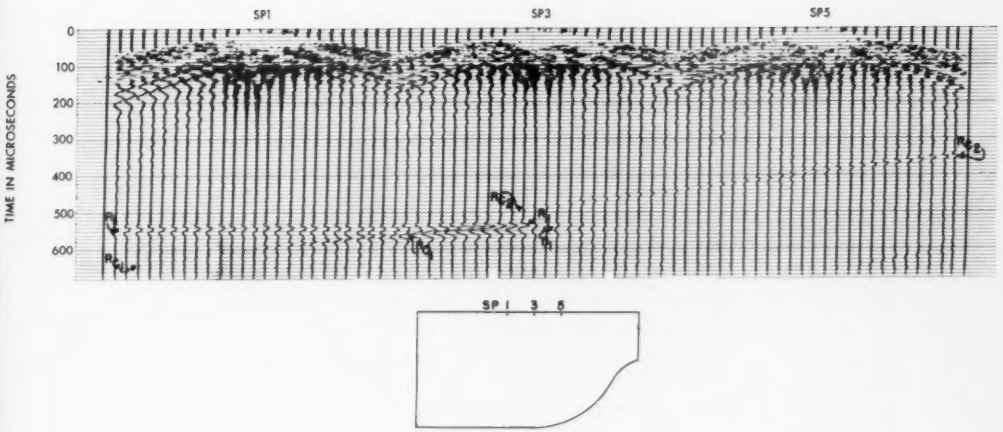


FIG. 8. A continuous profile shot over a curved surface with a buried focus.

the geometry of the model which produced them. However, when the geometries are combined, the resulting model records approach the complexity of a field seismogram. The two geometries of Figure 9 were shot under identical conditions. Shotpoints were located directly above the fault and 6 in to either side of it. A continuous profile was shot over each of the models. These records are presented in Figure 10. As before, the reflections from the flat reflectors are labeled as $R_H$, $R_L$, and $R_b$, the curved surface reflections as $R_{C_1}$ and $R_{C_2}$, and the diffractions by $D$.

The increased complexity of the model C record is quite apparent. The fault can be easily located below shotpoint 0 for model A; however, a migration or wave front technique must be employed to locate the fault of model C at shotpoint 0.

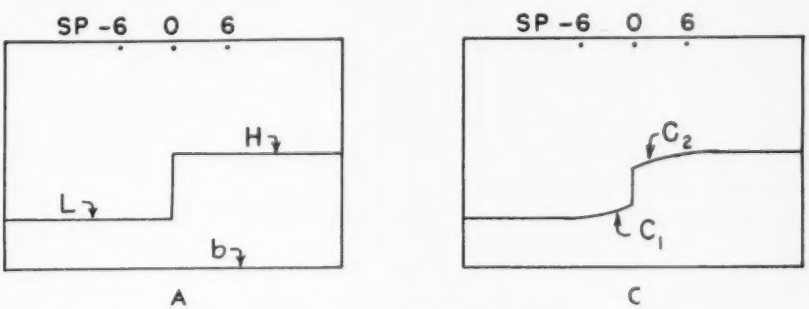


FIG. 9. Models A and C are similar except for the addition of curved interfaces leading to and from the fault for model C.

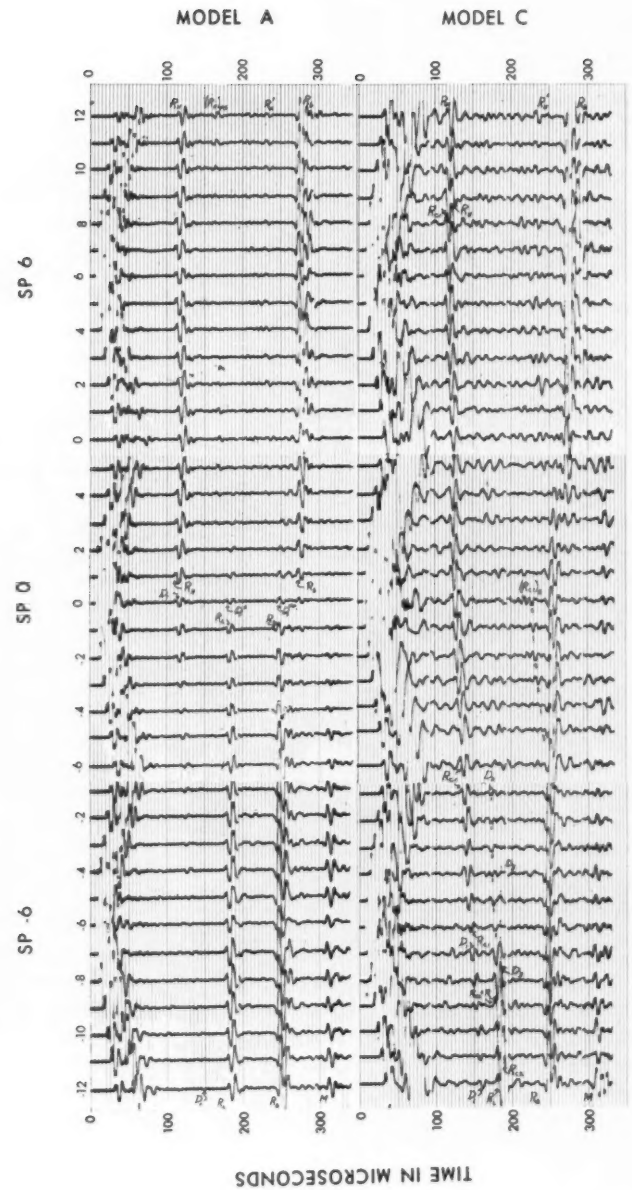


FIG. 10. Continuous profile shot over models A and C.

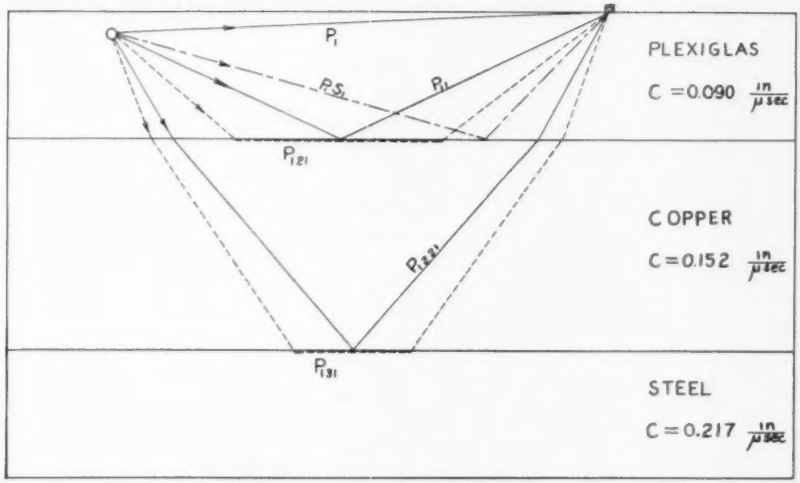


FIG. 11. A simple refraction model.

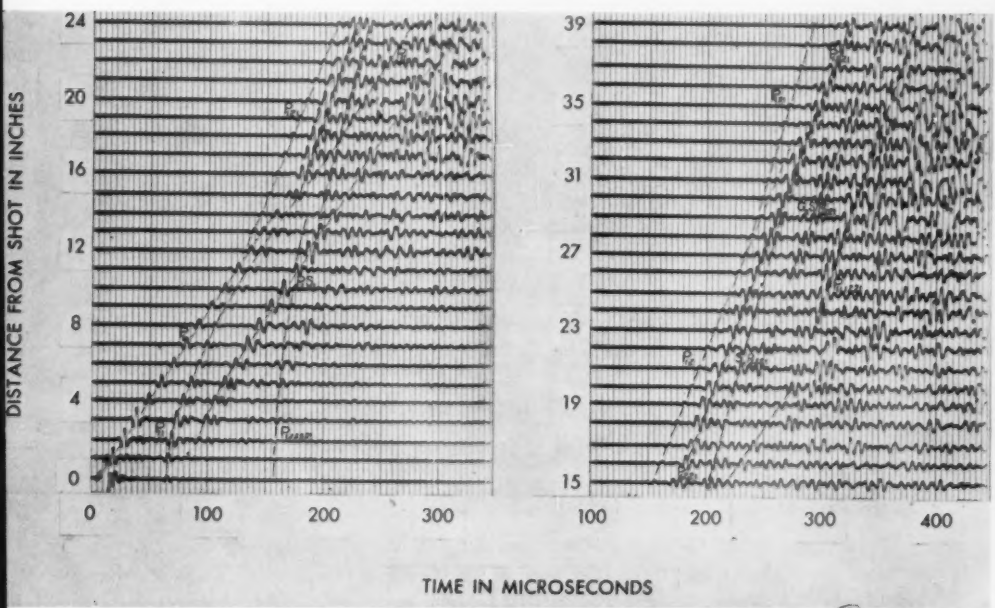


FIG. 12. Refraction records showing later arrivals.

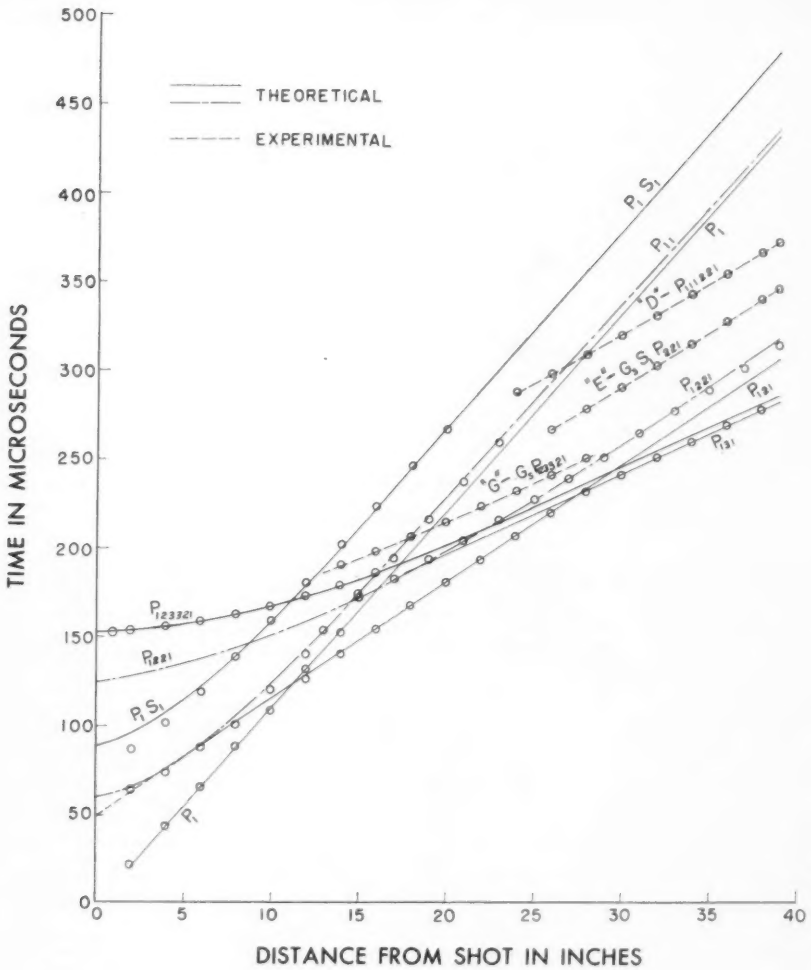


FIG. 13. Travel time curves from refraction records.

*Refraction Model*

The final model to be discussed demonstrates the application of two-dimensional modeling to the refraction process. A simple three-layer model is shown in Figure 11. The shot was fixed at SP 1 and records were taken with spreads extending from the shotpoint to a point 24 in to the right and another extend-

ing from 15 to 39 in to the right. The refraction records are presented in Figure 12.

The copper refraction comes in as the first arrival from station 12 to 28 where the refraction from the steel takes over. These refractions give velocities of 0.151 in/microsec for copper and 0.215 in/microsec for steel. These both are within one percent of the value measured directly by the transit time technique. A number of later events are picked and identified on the time-distance plot of Figure 13. The largest events on the records are the copper reflection $P_{1221}$ and the events $E$ and $D$ which are this same reflection but delayed due to a portion of the path traversed at shear velocity.

ACKNOWLEDGMENT

The author wishes to thank the Socony Mobil Company for permission to publish this material. Appreciation is also expressed to J. Podhrasky for assistance in the fabrication of the models and to C. W. McRight in the preparation of the model seismograms.

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GEOPHYSICS, VOL. XXV, NO. 2 (APRIL, 1960), PP. 483–504, 1 FIG.

# PLANE COMPRESSIONAL VOIGT WAVES*

FRANCIS COLLINS†

## ABSTRACT

The Voigt wave equation, long considered a possible mathematical model for seismic waves, was extensively studied in 1943 by Norman Ricker, who developed an asymptotic solution applicable at sufficiently large distances from the shotpoint. Ricker's solution does not agree with his field results (1953) in all respects. For example, Van Melle (1954) has shown that Ricker's wavelets decay too rapidly with distance to be consistent with the experimental data. This particular difference between theory and observation may arise from the form of the wave source implicitly assumed by Ricker, a doublet impulse of displacement.

A single impulse of pressure seems a more reasonable first approximation to the shot. For this source a complete solution for plane waves is developed, valid for all distances and times. A method similar to Ricker's is then outlined for obtaining an asymptotic solution suitable for computations at large distances.

The wavelets from the pressure impulse do not decay as rapidly as Ricker's doublet displacement solutions. This is a move toward better agreement with experiment. On the other hand, the pressure impulse wavelets have only a single lobe, a definite move away from the observations. There is some reason to believe, however, that the corresponding spherical waves would be more oscillatory than the plane waves.

More mathematical work is needed for further tests of the Voigt solid as a theoretical model for earth waves. The next step suggested is the computation of spherical waves from a pressure impulse.

## SYMBOLS USED

$A$ = amplitude of the stress impulse, equation (5), etc.

$a$ = radius of spherical cavity, equations (56) and (57).

$c$ = compressional wave velocity in a thin bar, equations (7) to (52),
= dilatational velocity in an infinite solid, equations (56) and (57).

$D_{-n}(z)$ = parabolic cylinder function of negative integral order, equations (23) to (55).

$E$ = Young's modulus for a bar, equations (1) to (9).

$He_n(z)$ = Hermite polynomial of order $n$ based on $\exp(-z^2/2)$, equation (48).

$k = \sqrt{2/X}$, equations (37) to (47).

$P_n(t)$ = a polynomial in $t$ defined in terms of $p_n(s)$ by equation (50).

$p_n(s)$ = a polynomial in $s$, computed by the method described in connection with equations (37) to (47).

$q_n(s)$ = a polynomial in $s$, computed by the method described in connection with equations (40) to (44).

$r$ = spherical co-ordinate = distance from center of spherical cavity, equations (56) and (57).

$S = \sum_{n=3}^{\infty} a_n(ks)^{n-3}$, equations (41) to (44).

$s$ = complex variable introduced by application of the Laplace transform, equation (8).

$T$ = Ricker's dimensionless time = $\omega_0 t$, equations (25) to (52).

$t$ = time.

* Presented at the Twenty-ninth Annual Meeting, Los Angeles, November 9, 1959. Manuscript received by the Editor August 27, 1959.

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$U(t)$ = unit step function, zero for $t$ negative and one for $t$ positive.
$u$ = displacement of a point on the bar from its rest position, equations (2) to (13).
= Ricker's time variable, equations (26) to (49).
$v$ = velocity of a point of the bar (this is "particle velocity," not wave velocity), equations (3) to (52).
$v_r$ = radial particle velocity, equations (56) and (57).
$X = \omega_0 x/c$ = Ricker's dimensionless distance, equations (19) to (49).
$x$ = distance from the free end of the bar, equations (2) to (49).
$\gamma$ = propagation exponent, equations (14) to (56).
$\delta(t)$ = impulse function, equation (5).
$\epsilon$ = strain, equations (1) to (14).
$\lambda$ = Lamé constant.
$\mu$ = Lamé constant = rigidity.
$\rho$ = density, equations (3) to (57).
$\sigma$ = longitudinal stress in the bar, equations (1) to (16).
$\omega_0$ = Ricker's transition frequency, equations (1) to (57).

## INTRODUCTION

"Voigt solid" appears to be the most widely used term for a material in which stress is the sum of two terms, one proportional to strain and one to rate of strain. Ricker (1943) attributes this mathematical model to Stokes, while others, such as Mattice and Lieber (1954), trace it to Kelvin. Regardless of the terminology, we can avoid misunderstanding by explicitly writing down the stress-strain relation. A full statement with all components would require a substantial array of equations. Since we treat here plane compressional waves only, we need simply the stress-strain relation for a bar,

$$\sigma = E\left(\epsilon + \frac{1}{\omega_0}\frac{\partial \epsilon}{\partial t}\right). \tag{1}$$

Here $\sigma$ and $\epsilon$ are stress and strain, $E$ is Young's modulus for the bar, and $t$ is time. The constant $\omega_0$ has been called the transition frequency by Ricker (1943). We have chosen to write the stress-strain relation (1) in a form so that this important parameter is directly displayed, and further we plan to follow Ricker's notation as far as possible without conflicting with well-established standard symbols.

In treating plane compressional waves it makes no difference whether we consider a very thin bar (whose diameter is a small fraction of the shortest wave length to be considered) or the more conventional infinite half-space. If we prefer to think in terms of the infinite half-space, we need only replace the Young's modulus $E$ in (1) by the combination $(\lambda+2\mu)$ of Lamé's constants $\lambda$ and $\mu$. The rest of the analysis will not be affected.

A stress-strain relation such as equation (1) can be combined with a purely

geometric strain-displacement relation and a very general force-acceleration relation to obtain a wave propagation equation for the material characterized by the stress-strain relation. That is, the stress-strain relation is the primary variable function in the mathematical model—the other relations involved are much more general and are rather firmly established. The Voigt wave equation corresponding to (1) has been extensively studied by Ricker (1943), and a check against field tests is claimed by Ricker (1953).

Criticisms of Ricker's analysis by Kaufman (1953), Van Melle (1954), and Collins and Lee (1956), and the recent field experiments of McDonal et al. (1958), are making it appear unlikely that the Voigt wave equation will turn out to be a good description of the propagation of stress-waves in the earth. There is thus some reason for abandoning the study of this particular mathematical model, at least temporarily. We have found, however, that previous mathematical treatments of this model are by no means complete. Some of the general conclusions appear a little misleading, or at least over-simplified.

The analysis which follows has also not been carried far enough to tell the whole story. There will be, however, enough to show that further numerical computation of wave shapes is needed, and to suggest that when these tables are computed they may significantly affect the comparison of theoretical results with field experiments. It will even appear that there is reason to suspect that some of the objections to Ricker's work may disappear in the light of the newer mathematical analysis.

The particular problem to be treated is that of a semi-infinite bar of Voigt material, defined by equation (1), which is struck a quick hammer blow at the free end. The bar is assumed to be of arbitrarily small diameter—we are not considering here the full problem of waves in a bar, but the simplified problem in which the waves are assumed to be plane waves. Alternatively, as previously mentioned, we can consider the problem as that of an infinite half-space in which plane waves are sent out by a hammer blow which is applied uniformly over the entire infinite free surface.

The hammer blow is chosen as a wave source because it seems physically similar to the real situation in seismic exploration. There are four interrelated quantities involved in a stress-wave problem—stress, strain, displacement, and velocity (this is velocity of particle motion at a given point, not velocity of wave propagation). In a mathematical analysis the source of the wave can be specified in terms of any one of these (or, conceivably, a combination of two or more). Which do we choose as most nearly resembling the physical situation? When we fire the charge at a shotpoint, do we seize the earth and cause it to move in a certain way (apply a displacement), do we give the surface a certain velocity, do we strain it in some way, or do we apply a force to it?

To us the answer seems fairly straightforward. We apply a force: we push, and then we see what happens to the displacement, the particle velocity, and the strain. It seems to us that the hammer blow, or the explosive charge, corresponds to a specification of the wave source in terms of pressure, or stress.

How shall we approximate the stress from the hammer blow as a function of time? The answer here is dictated purely by considerations of simplicity. We do not know what to assume, so we assume the simplest thing we can and work the easiest problem first. After we have fully explored the simplest problem we may then see that we need to solve some harder problems. The simplest assumption we can make is that the applied stress at the end of the bar is an impulse—an arbitrarily large stress which is applied for an arbitrarily short time. The simplicity lies in the fact that solutions of the wave equation can usually be obtained by assuming that the Laplace transform of such an impulse is unity. That is, the solution to the problem has some limiting form in which the applied stress is allowed to approach infinity while the time of application is allowed to approach zero. This limiting form of the solution can usually be obtained by taking the limit in the Laplace transform domain before inverting the transform to obtain the solution in the time domain.

It will be shown that this wave source, a stress impulse, is not the same as that used by Ricker in his mathematical development. This difference leads to a possibility of solutions which match the field experiments better than Ricker's solutions.

The next question is which of the four quantities (stress, strain, displacement, and particle velocity) we shall attempt to calculate as functions of time and distance along the bar. They are all of intrinsic interest, and from a broad viewpoint we cannot neglect any of them. For the present analysis, however, we choose to confine ourselves to the particle velocity as the quantity which is directly measured by an electromagnetic seismometer.

## THE PROBLEM

### (equations 1 to 6)

The problem just outlined will now be stated in definite mathematical terms. We consider a semi-infinite bar of Voigt material defined by the stress-strain relation (1). To this equation we add the strain-displacement relation and a balance of forces. For a bar of negligible thickness the strain-displacement relation is

$$\epsilon = \frac{\partial u}{\partial x}, \tag{2}$$

where $u$ is the displacement of a particle from its rest position and $x$ is distance measured from the free end of the bar. We note in passing that this is a linearized relation applicable to very small strains. This approximation is satisfactory but we should be aware that we have made it.

In balancing the forces on an element of a very thin bar, we consider only the normal stress $\sigma$ in the $x$-direction and the inertial force. Gravitational force in particular is neglected—again this is a satisfactory approximation which we wish

merely to take note of. On this basis we have a force-acceleration relation, a Newton's second law,

$$\frac{\partial \sigma}{\partial x} = \rho \frac{\partial v}{\partial t}, \tag{3}$$

in which $v$ is the particle velocity,

$$v = \frac{\partial u}{\partial t}, \tag{4}$$

and $\rho$ is the density of the material. In further operations with this equation, it will be assumed that the density is constant. The argument for this assumption is that density variations in a solid are small, despite the fact that the wave itself is propagated by means of density variations.

Finally, we have the initial and boundary conditions. The boundary condition or wave source, the hammer blow at $x=0$, is

$$\sigma(0, t) = A\delta(t), \tag{5}$$

where $\delta(t)$ is the so-called impulse function whose Laplace transform will be taken as unity. The factor $A$ is an arbitrary amplitude.

The initial conditions are simply that everything is at rest,

$$\sigma(x, 0) = \epsilon(x, 0) = u(x, 0) = v(x, 0) = 0. \tag{6}$$

In addition to the boundary condition at $x=0$, we add the condition that the wave must become small, or at least must not increase indefinitely, for large values of $x$.

The mathematical problem is now to find the solution of the differential system (differential equations plus boundary and initial conditions) defined by equations (1) to (6). We choose to seek first the expression for the particle velocity $v(x, t)$ rather than one of the other variables.

## GENERAL SOLUTION

### (equation 25)

One procedure is to begin by manipulating the differential equations (1) to (4), differentiating and substituting, to obtain a wave equation involving only one of the four unknown functions (stress, strain, displacement, velocity). We mention this approach because we wish to point out that, contrary to some published statements, these four quantities all satisfy the same wave equation,

$$\frac{\partial^2 z}{\partial x^2} + \frac{1}{\omega_0} \frac{\partial^3 z}{\partial x^2 \partial t} = \frac{1}{c^2} \frac{\partial^2 z}{\partial t^2}, \tag{7}$$

where $z$ may be any of the four quantities $\sigma$, $\epsilon$, $u$, or $v$, and $c$ is the compressional wave velocity for the bar, $c^2 = E/\rho$.

When using the Laplace transform, however, it is not necessary or even desirable to work with this wave equation. It is probably simpler to apply the transform directly to equations (1) to (5), making use of (6) wherever it is needed.

We perhaps should explicitly define the Laplace transform which we wish to use. For later development of the asymptotic solution, it will be convenient to deal with the two-sided transform in the sense of van der Pol and Bremmer (1950). We do not, however, follow van der Pol and Bremmer in using a "*p*-multiplied" transform. Thus we use a transform which converts a function of time $f(t)$ into a function $\boldsymbol{f}(s)$ of a complex variable $s$ according to the formula

$$\boldsymbol{f}(s) = \int_{-\infty}^{\infty} f(t)e^{-st}dt. \tag{8}$$

This is of course only a generalization of the Fourier transform, a generalization convenient rather than essential in the present problem, which could be handled in terms of the Fourier integral.

In using this two-sided transform it is necessary to identify a one-sided time function (one which is zero for negative values of $t$) by including the factor $U(t)$, the unit step function which is zero for $t$ negative and one for $t$ positive. For example, the two-sided transform $1/(s+1)$ has the inverse $U(t)e^{-t}$. We could not write this inverse simply as $e^{-t}$, for this function has no two-sided transform. This is a crucial point in initial value problems—the presence of the factor $U(t)$ shows that the function is zero for negative values of $t$.

We apply this Laplace transform to equations (1) to (5), in each case using bold type to indicate the transform of a function with respect to the time $t$. This procedure leads to the following differential system involving four transforms of the four unknown functions,

$$\boldsymbol{\sigma} = E\left(1 + \frac{s}{\omega_0}\right)\boldsymbol{\varepsilon}, \tag{9}$$

$$\boldsymbol{\varepsilon} = \frac{\partial \boldsymbol{u}}{\partial x}, \tag{10}$$

$$\frac{\partial \boldsymbol{\sigma}}{\partial x} = \rho s \boldsymbol{v}, \tag{11}$$

$$\boldsymbol{v} = s\boldsymbol{u}, \tag{12}$$

$$\boldsymbol{\sigma}(0, s) = A. \tag{13}$$

In these equations $\boldsymbol{\sigma}$, $\boldsymbol{\varepsilon}$, $\boldsymbol{u}$, and $\boldsymbol{v}$ are functions of $x$ and $s$. Since derivatives with respect to $s$ do not appear, however, the system can essentially be treated as a set of ordinary differential equations, the independent variable being $x$, and $s$ being treated as a constant.

Although we wish to solve for $\boldsymbol{v}(x, s)$ and then for $v(x, t)$, it will be easier

to apply the boundary condition (13) if we first obtain an expression for $\sigma(x,s)$. To eliminate the other three transforms from (9) to (12), proceed as follows. Eliminate $v(x, s)$ between (11) and (12). Use this result with (10) to eliminate $u(x, s)$. Finally, use this second result with (9) to eliminate $\varepsilon(x, s)$. We thus obtain a differential equation for $\sigma(x, s)$,

$$\frac{\partial^2\sigma}{\partial x^2} = \gamma^2\sigma, \tag{14}$$

where the propagation exponent $\gamma(s)$ is defined by

$$\gamma^2 = \frac{s^2}{c^2\left(1 + \frac{s}{\omega_0}\right)}, \tag{15}$$

$c$ being the compressional wave velocity in the bar, $c^2 = E/\rho$.

The solution of this equation which remains finite for large values of $x$ and satisfies (13) at $x=0$ is

$$\sigma = Ae^{-\gamma x}. \tag{16}$$

We differentiate this expression once with respect to $x$ and substitute in (11) to obtain the velocity transform,

$$v = -\frac{A\gamma}{\rho s}e^{-\gamma x}. \tag{17}$$

We could now use this expression for direct calculation of the frequency spectrum of the velocity wavelet at any distance $x$ by putting $s = i2\pi f$ and evaluating the magnitude and phase for various values of the frequency $f$. We are primarily interested, however, in inverting the transform (17) into the time domain to obtain $v(x, t)$ in a form such as to permit the calculation of the wave shape at any distance $x$.

In carrying out this operation it will be useful to adopt the symbol used by van der Pol and Bremmer to connect a function with its transform,

$$v(x, t) \doteqdot v(x, s). \tag{18}$$

The upper dot is written on the side toward the time function, and the lower dot on the side toward the transform. This notation simplifies keeping a record of the effects of the application of operational rules. For example, we first wish to replace $s$ by $\omega_0 s$ in (17) in order to simplify the square root in the expression for $\gamma(s)$ which appears twice in (17). We then have

$$\frac{1}{\omega_0}v\left(x, \frac{t}{\omega_0}\right) \doteqdot -\frac{A}{\rho c}\frac{\exp\frac{-Xs}{\sqrt{1+s}}}{\sqrt{1+s}}, \tag{19}$$

in which the effect of this elementary operation in the time domain is explicitly set forth (multiplying by $1/\omega_0$ and replacing $t$ by $t/\omega_0$). In this expression it has been convenient to adopt Ricker's dimensionless distance, $X=\omega_0 x/c$. Later we shall also use Ricker's dimensionless time, $T=\omega_0 t$.

The next operation on (19) is to replace $s$ by $s-1$ to further simplify the square roots. This operation on the transform multiplies the inverse by $\exp t$, so that the result is

$$v\left(x, \frac{t}{\omega_0}\right) e^t \doteqdot -\frac{A\omega_0 \exp\left(-X\sqrt{s}+X/\sqrt{s}\right)}{\rho c \sqrt{s}} . \tag{20}$$

We separate the exponential function into two factors and write the second as an infinite series,

$$e^{X/\sqrt{s}} = \sum_{n=0}^{\infty} \frac{X^n}{n!(\sqrt{s})^n} . \tag{21}$$

Substituting this expression in (20), we obtain

$$v\left(x, \frac{t}{\omega_0}\right) e^t \doteqdot -\frac{A\omega_0}{\rho c} \sum_{n=0}^{\infty} \frac{X^n}{n!} \frac{e^{-X\sqrt{s}}}{(\sqrt{s})^{n+1}} . \tag{22}$$

This is one of those cases in which the transform may be expanded in a series which converges for all values of $s$, and after term by term inversion, the resulting time function converges for all values of $t$. We are able to invert (22) term by term by referring to the Bateman Manuscript Project *Tables of Integral Transforms* by Erdélyi et al. (1954), volume 1, page 246, formula 9, which, after suitable substitutions for the parameters, gives

$$\frac{e^{-X\sqrt{s}}}{(\sqrt{s})^{n+1}} \doteqdot \frac{U(t)}{\sqrt{\pi}} (\sqrt{2})^n (\sqrt{t})^{n-1} e^{-X^2/8t} D_{-n}\left(\frac{X}{\sqrt{2t}}\right). \tag{23}$$

In this expression the $D_{-n}(z)$ are the parabolic cylinder functions of negative integral order.

We apply (23) to each term of (22) and obtain a series of functions of $t$ which converges for all values of $t$,

$$v\left(x, \frac{t}{\omega_0}\right) e^t = -U(t) \frac{A\omega_0}{\rho c} \sum_{n=0}^{\infty} \frac{X^n 2^{n/2} t^{n/2}}{n!\sqrt{\pi t}} e^{-X^2/8t} D_{-n}\left(\frac{X}{\sqrt{2t}}\right). \tag{24}$$

To obtain $v(x, t)$ we replace $t$ by $\omega_0 t$, that is to say by Ricker's dimensionless time $T$, getting

$$v(x, t) = -U(t) \frac{A\omega_0}{\rho c\sqrt{\pi}} \frac{1}{\sqrt{T}} e^{-T-X^2/8T} \sum_{n=0}^{\infty} \frac{(X\sqrt{2T})^n}{n!} D_{-n}\left(\frac{X}{\sqrt{2T}}\right). \tag{25}$$

This is the general solution of the differential system (1) to (6); that is, (25) gives an explicit expression, valid for all values of $x$ and $t$, for the velocity wavelet in a bar of Voigt material after an impulse of stress is applied at the free end (at $x=0$, $t=0$).

This derivation illustrates the engineering applications of the mathematical material which is becoming available in organized and tabulated form so that it can be used without a detailed knowledge of the special functions involved. We will later refer to more such material for information needed to calculate the series of parabolic cylinder functions appearing in (25).

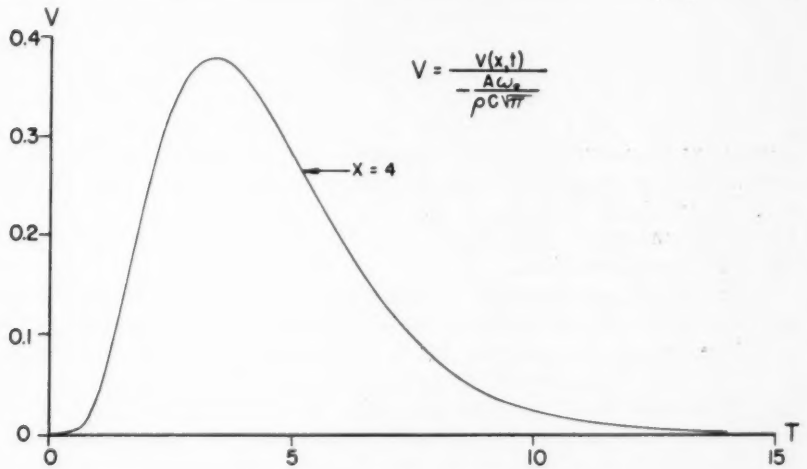


FIG. 1. Velocity-type wavelet produced in a thin semi-infinite Voigt bar by a pressure impulse at the free end. This is the wavelet calculated from the general solution (25) at a dimensionless distance $X=4$. Dimensionless distance is $X=\omega_0 x/c$ and dimensionless time is $T=\omega_0 t$, where $c$ is the wave propagation velocity in the bar and $\omega_0$ is Ricker's transition frequency which characterizes the Voigt solid. A Voigt solid is defined by equation (1), in which energy loss is introduced by making stress equal to the sum of strain and strain-rate terms.

Even the casual reader will also recognize another feature of this derivation, namely that a published analysis of this kind rarely shows the processes by which it was deduced. That is, formula (23) and its ready application were not discovered on the first day of work. Indeed, progress from equation (17) to equation (25) was made by several different routes, all complex and laborious. The alternative methods have some intrinsic interest, and possibly greater interest as an example of the stumbling progress of some research. To quote de Bruijn (1958), however, "a mathematician cannot possibly publish his waste-paper basket"; engineers are also subject to this restriction, so we will omit the reams and quires which preceded the simple procedure outlined above.

We now note some of the features of the general solution (25). First, enough numerical calculation has been done to show that the wavelet shapes consist of a single lobe or excursion away from zero. This characteristic is not promising for comparison with the two-lobe wavelets observed by McDonal et al. (1958), and still less for comparison with Ricker's multiple-lobe wavelets. There is some reason, however, for believing that if the corresponding spherical wave case could be solved the wavelets would have more than one lobe. This matter will be discussed later.

Second, the general solution (25) can by no means be suitably written in terms of Ricker's time variable $u$, which is defined by

$$u = \frac{T - X}{\sqrt{\frac{X}{2}}}. \tag{26}$$

That is, we cannot replace the time variable $T$ by $u$ without having an extra term in $X$ occurring along with the variable $u$, although of course having computed values of $v(x, t)$ we can plot them as functions of $u$ for any $x$ if we wish. This condition suggests that Ricker's solutions are not general but must have some special interpretation.

Third, preliminary inspection suggests and numerical work confirms that the general solution (25) is suitable for calculation only for fairly small values of $X$ and $T$, very roughly we might say for $X$ less than five or ten. Hence we turn our attention to the development of an asymptotic series which can be used to calculate the wavelet shapes $v(x, t)$ for large values of $X$ and $T$. In so doing we will throw some light on the nature of Ricker's solutions.

## ASYMPTOTIC SOLUTION

### (equations 32 and 49)

The development of an asymptotic series for a given function can be approached in various ways. Systematic surveys of methods by Erdélyi (1956) and de Bruijn (1958) have recently become available. A simple method is fortunately adequate for the present problem. We can develop an asymptotic series for the velocity wavelet $v(x, t)$ by starting with its Laplace transform given by equation (19).

The general idea is that the behavior of the time function $v(x, t)$ for large values of $t$ corresponds to the behavior of the transform $v(x, s)$ for small values of $s$. More particularly, this turns out to be one of the cases in which the transform can be expanded in a series which converges only for small values of $s$. This series can be inverted term by term to obtain an asymptotic series suitable for calculating $v(x, t)$ for large values of $t$.

The key idea is again the simplification of the square roots in (19), this time by expanding them in a series of ascending powers of $s$,

$$\frac{1}{\sqrt{1+s}} = 1 - \tfrac{1}{2}s + \tfrac{3}{8}s^2 - \cdots \tag{27}$$

This series converges only for sufficiently small values of $s$, specifically only for $s<1$. We may anticipate, therefore, that a transform containing this series, when inverted, will yield a time function which is satisfactory for sufficiently large values of $t$.

*First term of asymptotic series (equation 32)*

Before working out the complete series, let us clarify our ideas by examining only the first term, whose inverse will give the final form of the velocity function $v(x, t)$ as $t$ approaches infinity. For this purpose, we insert two terms of the square root expansion (27) in the exponent which occurs in (19), and one term of (27) in the denominator of (19). At first glance, it appears that we are thus approximating the same function to two different degrees of precision. This procedure is justified because of the fundamentally different effects that the square root has in the exponent and in the denominator. In the exponent, the first term of the expansion introduces nothing but a time shift; it does not even hint at the effect of the branch point at $s=-1$ which is crucial in determining the wave shape. Hence the second term must be included. In the denominator of (19), however, inclusion of the second term of (27) is not essential to determining the final wave shape; the second term adds a time function whose contribution ultimately becomes negligible in comparison with that from the first term. This condition will be apparent when we develop the complete series.

Proceeding on the basis, then, of inserting two terms of (27) in the exponent of (19) and one term of (27) in the denominator of (19), we have

$$v\left(x, \frac{t}{\omega_0}\right) \doteqdot -\frac{A\omega_0}{\rho c} e^{-Xs} e^{(X/2)s^2}. \qquad \begin{pmatrix} s \to 0 \\ t \to \infty \end{pmatrix} \tag{28}$$

As mentioned above, the factor $\exp(-Xs)$, which comes from the first term of (27), contributes only a time shift to the inverse transform. We can drop this factor from the right-hand side of (28) if we add $X$ to the time variable on the left-hand side, so that

$$v\left(x, \frac{t+X}{\omega_0}\right) \doteqdot -\frac{A\omega_0}{\rho c} e^{(X/2)s^2}. \qquad \begin{pmatrix} s \to 0 \\ t \to \infty \end{pmatrix} \tag{29}$$

This arrangement corresponds to the fact that the principal part of the wave occurs in the neighborhood of $t=x/c$, or $T=X$, for, after inverting the right-hand side of (29) into a time function, we obtain $v(x, t)$ by replacing $t$ by $T-X$. Time is then conveniently measured on both sides of the point $T=X$.

We now consider the question of inverting the transform in (29), and we come upon the advantage of using the two-sided transform. In tables of one-sided transforms we search in vain for the inverse of $\exp s^2$; it does not exist. If

we look into transform theory we can see this result at once from the order properties—the transform of a one-sided function must vanish as $s$ approaches infinity.

But if we consult tables of two-sided transforms we find that (29) is a member of a key pair,

$$e^{\alpha s^2} \doteqdot \frac{1}{2\sqrt{\pi\alpha}}\, e^{-t^2/4\alpha}. \tag{30}$$

One of the readiest sources for this formula is Campbell and Foster (1942), page 85, no. 710.1. The unit step function $U(t)$ is absent; equation (30) is valid only if the right-hand side is integrated over both positive and negative values of $t$. We apply (30) to (29) by putting $\alpha = X/2$, and the result is

$$v\left(x, \frac{t+X}{\omega_0}\right) \sim -\frac{A\omega_0}{2\sqrt{\pi}\rho c}\sqrt{\frac{2}{X}}\, e^{-t^2/2X}. \qquad (t \to \infty) \tag{31}$$

To obtain $v(x, t)$ we compensate for previous elementary operations on the transform by replacing $t$ by $\omega_0 t - X$ throughout (31). We then have the ultimate form of the velocity wavelet for very large values of $t$,

$$v(x, t) = -\frac{A\omega_0}{2\sqrt{\pi}\rho c}\sqrt{\frac{2}{X}}\, e^{-u^2/4}, \qquad (t \to \infty) \tag{32}$$

where, to repeat the less obvious notational definitions,

$$u = \frac{T - X}{\sqrt{\frac{X}{2}}}, \qquad \text{(Ricker's time variable)} \tag{33}$$

$$X = \omega_0 x/c, \qquad \text{(Ricker's dimensionless distance)} \tag{34}$$

$$T = \omega_0 t. \qquad \text{(Ricker's dimensionless time)} \tag{35}$$

Like the general solution (25), equation (32) represents a single lobe or excursion away from zero. It is symmetrical about the point $X = T$ (or $u = 0$). The fact that solutions of this form can correspond only to sufficiently large values of $t$ is emphasized by the absence of the unit step function $U(t)$ which would cut the function off at $t = 0$. Equation (32) gives non-zero values of $v(x, t)$ for negative values of $t$; that is, the initial conditions (6) are not satisfied, or the wave starts before the hammer strikes the bar. But for large values of $t$, the wavelet described by (32) drops off rapidly on each side of the point $T = X$, and the fact that it does not give an absolute zero value for negative $t$ is of no consequence in numerical evaluation.

When the method for deriving (32) is compared with the procedure of Ricker (1943), it is evident that Ricker's solution is essentially an asymptotic result

suitable for computation for large values of time; as he says, it is "obtained not through a development about the shotpoint, but about the point at infinity." By using the language of the two-sided Laplace transform, we have been able to explain how Ricker was able to obtain a useful solution with the binomial expansion (27), despite its restricted region of convergence.

We now compare the first term of the asymptotic solution, equation (32), with the corresponding first term of the solution for the velocity wavelet given by Ricker (1943, equations 34 and 49), namely

$$v(x, t) \sim -\frac{\sqrt{\pi}}{2}\left(\frac{2}{X}\right)^{3/2}\left(\frac{u^2}{4}-\frac{1}{2}\right)e^{-u^2/4}. \quad \text{(Ricker)} \tag{36}$$

Some of the features are listed below.

| | *Equation (32)* | *Equation (36)—Ricker* |
|---|---|---|
| Wavelet breadth increases as | $X^{1/2}$ | $X^{1/2}$ |
| Amplitude decreases as | $X^{1/2}$ | $X^{3/2}$ |
| Number of lobes | 1 | 3 |
| Wave source (stress input) | Impulse | Triplet impulse |

Ricker did not specify the form of the input which he used—he considered the solution as developed to match observed wavelets at large distances from the shot. No matter what viewpoint is used in developing a solution, however, it does correspond to *some* form of input. By a little experimentation, we find that we can arrive at Ricker's solution (36) if we start with a triplet impulse of stress or pressure as an input at the free end of the bar ($x=0$).

(Considering only the first term of Ricker's solution, given by (36), we cannot distinguish between three possible wave sources, a triplet impulse of stress, a doublet impulse of displacement, or a triplet impulse of velocity. Each of these three sources leads to (36) as the first term of the asymptotic series. When we consider more terms of the asymptotic expansion, however, we find that Ricker's complete asymptotic series corresponds either to a doublet impulse of displacement or a triplet impulse of velocity; a triplet impulse of stress would lead to a slightly different series. For comparing equations (32) and (36), however, it is accurate and probably more instructive to think in terms of the stress sources which would produce these two results.)

Can we at this point say anything about the possibility that the single impulse solution, given in general by (25) and for very large values of $t$ by (32), will match experimental data better than Ricker's triplet impulse solution, given for very large values of $t$ by (36)? There is one encouraging feature of the new solution—the wavelet amplitude falls off more slowly than in Ricker's solution. *This is at least in the direction of meeting the objection to Ricker's solution raised by Van Melle (1954).*

The most discouraging feature of the new solution is that it has only one lobe. This may be a move in the wrong direction, for even Ricker's three-lobe wavelets are not sufficiently oscillatory to match his field data. The recent data

of McDonal et al. (1958), however, suggest that two lobes may be more nearly representative of observed wavelets. And we feel that there is a possibility that a single stress impulse may lead to wavelets with more than one lobe if we can work out the solution for spherical rather than plane waves.

A complete study of the wavelet shapes must be based on calculations with equation (25) for small values of $X$ and $T$, calculations with an asymptotic series for intermediate values, and finally calculations with (32) to which the asymptotic series reduces for very large values of $X$ and $T$. (Equation (32) fundamentally applies for large values of $T$. We immediately fall into the habit of speaking of large values of $X$ and $T$ since the wavelet (32) is centered at $X=T$ and the two variables have the same order of magnitude when both are large.)

*Method for complete asymptotic series (equations 37 to 49)*

We now proceed with the complete asymptotic series. Guided by Ricker's results and by the above analysis of the first term, we start out with the idea that we can develop a series of terms with descending powers of $X$ and time functions containing only the variable $u$. To this end, before expanding the square roots in (19), we replace $s$ by $ks$, compensating in the time domain by multiplying by $1/k$ and replacing $t$ by $t/k$. If we choose $k=(2/X)^{1/2}$, it will be possible for us to arrange the expansion of (19) so that each term consists of a power of $X$ (or $k$) and a function of $s$ which does not contain $X$. This isolation of the descending powers of $X$ (or ascending powers of $k$) will simplify the term by term inversion of the expanded transform. The first modification of (19) in accordance with this plan gives

$$\frac{1}{\omega_0 k}\, v\left(x, \frac{t}{\omega_0 k}\right) \doteqdot -\frac{A}{\rho c}\, \frac{\exp \dfrac{-Xks}{\sqrt{1+ks}}}{\sqrt{1+ks}}. \tag{37}$$

We now require the complete expansion for the square root,

$$\frac{1}{\sqrt{1+z}} = 1 - \tfrac{1}{2}z + a_2 z^2 + a_4 z^3 + a_5 z^4 + \cdots, \quad z < 1, \tag{38}$$

where the coefficients are given by

$$a^n = (-1)^{n+1}\frac{1\cdot 3\cdot 5\cdots(2n-3)}{2\cdot 4\cdot 6\cdots(2n-2)} = \frac{(-1)^{n+1}(2n-2)!}{2^{2n-2}(n-1)!^2}. \tag{39}$$

The notation for these coefficients, the $a$'s, is the same as Ricker's except for the signs.

The next step is to use (38) to expand the exponent in (37). To save writing the complete expression, we can for the moment deal with the exponent only,

$$\frac{-Xks}{\sqrt{1+ks}} = -Xks + \tfrac{1}{2}Xk^2s^2 - a_3 Xk^3 s^3 - a_4 Xk^4 s^4 - \cdots, \tag{40}$$

or, after $X$ is replaced by $2/k^2$ in all but the first term,

$$\frac{-Xks}{\sqrt{1+ks}} = -Xks + s^2 - 2ks^3 \sum_{n=3}^{\infty} a_n (ks)^{n-3}. \tag{41}$$

If we represent the summation indicated in (41) by a single symbol $S$, we can write (37) in the form

$$v\left(x, \frac{t}{\omega_0 k}\right) \doteqdot -\frac{A\omega_0}{\rho c} \frac{ke^{-Xks} e^{s^2} e^{-2ks^3 S}}{\sqrt{1+ks}} \cdot \qquad \begin{pmatrix} s \to 0 \\ t \to \infty \end{pmatrix}. \tag{42}$$

The first exponential in (42), $\exp(-Xks)$, represents the time shift, and as in (28) we eliminate it and, according to an elementary operational rule of the transform, compensate by replacing $t$ by $t+Xk$ in the time function. The second exponential, $\exp s^2$, we retain as a common factor in each term of the expansion we are working toward.

The third exponential in (42), $\exp(-2ks^3S)$, we expand in ascending powers of $k$ (which is descending powers of $X$), the coefficient of each power of $k$ being a polynomial in $s$. This expansion can be carried out in two different ways. One plan is to consider first the individual terms of $-2ks^3S$, use these to write the exponential as the product of an infinite number of simpler exponentials, expand each of these, and multiply term by term. We choose the other direction, which is first to expand the exponential treating $-2ks^3S$ as a single term,

$$e^{-2ks^3S} = 1 - 2ks^3S + \frac{(2ks^3S)^2}{2!} - \frac{(2ks^3S)^3}{3!} + \cdots, \tag{43}$$

second to consider $2ks^3S$ as a series of terms, and finally to compute the powers of $2ks^3S$ in (43) by some form of the multinomial theorem, for example that given by Adams (1939) in the Smithsonian Tables, page 120. In this final step we proceed not by completely expanding any one term of (43) as a multinomial, but instead by computing one by one the complete coefficients of $k^n$ for successive values of $n$. That is, we can compute the contribution which any one term $(-1)^m(2ks^3S)^m/m!$ of (43) will make to the coefficient of $k^n$ without computing the complete expansion of the term. This work can be arranged systematically. It then becomes straightforward and tedious, and there seems nothing to be gained by detailing it further. Likewise, although we can write a general expression for the coefficient of $k^n$ by using a sufficiently complex and specialized notation, there seems little point in doing so. For numerical work we will compute as many terms as we need and the general term will be of no theoretical or numerical interest. The form of the result may be indicated as

$$e^{-2ks^3S} = 1 + q_1(s)k + q_2(s)k^2 + q_3(s)k^3 + \cdots, \tag{44}$$

where the $q$'s are polynomials in $s$.

In addition to dealing with the exponentials in (42) as outlined, we also ex-

pand the square root in the denominator according to (38), obtaining

$$\frac{1}{\sqrt{1+ks}} = 1 - \tfrac{1}{2}ks + a_3(ks)^2 + a_4(ks)^3 + \cdots, \tag{45}$$

and in fact before returning to (42) we may conveniently multiply (44) by (45) to get the combined expression

$$\frac{e^{-2ks^2S}}{\sqrt{1+ks}} = 1 + p_1(s)k + p_2(s)k^2 + p_3(s)k^3 + \cdots, \tag{46}$$

where the $p$'s are polynomials in $s$ obtained from multiplication of the series (44) and (45). Again we could write the general coefficient $p_n(s)$ in terms of the $q$'s and the $a$'s but there seems no need to do so.

We are now ready to operate on (42), inserting (46) and at the same time allowing for the time shift factor exp $(-Xks)$. The result is

$$v\left(x, \frac{t+Xk}{\omega_0 k}\right) \doteq -\frac{A\omega_0}{\rho c}\left[ke^{s^2} + k^2p_1(s)e^{s^2} + k^3p_2(s)e^{s^2} + \cdots\right]. \tag{47}$$

Here we have reached our goal of arranging (19) as a series of ascending powers of $k$ (descending powers of $X$). This series represents the velocity wavelet only for small values of $s$, or large values of $t$. It is suitable for term by term inversion to obtain a series of time functions whose coefficients are ascending powers of $k$, for (47) is arranged so that $k$ occurs only where it explicitly appears therein—the occurrence of $k$ will not be affected by the inversion process.

Since the $p$'s are polynomials in $s$, the inversion of (47) requires the time functions corresponding to transforms of the form $s^n \exp s^2$. The specific formulas for $n=0$ to $n=4$ are written out by Campbell and Foster (1942), no. 710.0 to 710.4, and the general case, which we repeat in slightly modified form, is given in no. 709.0,

$$s^n e^{s^2} \doteq \frac{(-1)^n}{\sqrt{\pi}(\sqrt{2})^{n+2}} He_n\left(\frac{t}{\sqrt{2}}\right) e^{-t^2/4}, \tag{48}$$

where $He_n(z)$ is the Hermite polynomial of order $n$ based on exp $(-z^2/2)$. Ricker's $G_n$-functions are essentially Hermite polynomials.

We see, then, that the inversion of any term of (47) will give a power of $k$ multiplied by a polynomial in $t$ and the exponential exp $(-t^2/4)$. Examination of the time variable on the left of (47) shows, and not to our surprise, that to recover the velocity wavelet $v(x, t)$ it will be necessary, after inversion, to replace $t$ throughout by Ricker's variable $u$ defined by (33). We thus find that the inversion of (47) gives us an expression for $v(x, t)$ consisting of a series of terms with descending powers of $X$, each term containing in addition a polynomial in $u$ and the exponential exp $(-u^2/4)$.

$$v(x, t) = -\frac{A\omega_0}{\rho c\sqrt{\pi}}\left(\frac{2}{X}\right)^{1/2}\left[\frac{1}{2} + \left(\frac{2}{X}\right)^{1/2} P_1(u) + \left(\frac{2}{X}\right)^{2/2} P_2(u) + \cdots\right] e^{-u^2/4}, \quad (49)$$

where $P_n(t)$ is the polynomial arising from the inversion of one of the terms of (47),

$$p_n(s)e^{s^2} \doteqdot \frac{1}{\sqrt{\pi}} P_n(t)e^{-t^2/4}. \quad (50)$$

The factor $\sqrt{\pi}$ has been included in this definition so that the constant factor in (49) will be the same as that in the general solution (25).

The terms of this series are of course quite similar to Ricker's wavelet functions. They differ only because we have used a single stress impulse as input while Ricker used either a doublet impulse of displacement or a triplet impulse of velocity.

By comparing the foregoing discussion with Ricker (1943), we find that we have essentially repeated Ricker's analysis, with the modifications needed to fit the input function we selected. In so doing, we have perhaps made a gain in precision by using the two-sided Laplace transform. The application of the transform has enabled us to show that Ricker's solution is essentially an asymptotic one applicable at sufficiently large distances and times. We can compare the asymptotic solution with the general solution (25), and after sufficient numerical work we can find where the asymptotic solution begins to be sufficiently accurate (within the width of a line on a graph, for example).

In addition, we now see how to construct solutions for simple input or source functions, and we at least know how to attack the problem for any given input function.

## NUMERICAL RESULTS

Unfortunately this section must consist more of a list of the computations we have yet to make than an exhibit of those which we have completed. The schedule for this work is rather indefinite, however, and it seems undesirable to further postpone publication of the theory.

The velocity wavelet $v(x, t)$ given by the general solution (25) has been computed for the dimensionless distance $X=4$ and is shown in Figure 1. Even at this small distance the wavelet is showing its tendency to center about the point $T=X=4$, the wavelet peak actually occurring close to $T=3.4$. The peak value of the wavelet is about 0.38, which is already not far from the value 0.35 given by the first term of the asymptotic expansion, equation (32). We are not yet prepared, however, to say that the asymptotic series will apply for this small value of $X$.

For a complete study we should compute wave shapes at enough values of $X$ so that we can at least determine the following:

(1) The distance at which the asymptotic series becomes sufficiently accurate for plotting graphs, and the number of terms of the series required at this distance.

(2) The distance at which the first asymptotic term alone, given by (32), is sufficient.

(3) The variation of wavelet breadth with distance. For comparison with field experiments, it may be important to know how far this variation departs, at small values of $X$, from the increase with $X^{1/2}$ which occurs at large values of $X$.

(4) The variation of wavelet peak amplitude with distance. At large distances the amplitude decreases in proportion to $X^{1/2}$. How far it departs from this variation at small values of $X$ may be important in such matters as that discussed by Van Melle (1954).

Incidentally, we can obtain the velocity wavelet shape at the end of the bar quite easily by setting $X=0$ in (19), so that

$$v\left(0, \frac{t}{\omega_0}\right) \doteq -\frac{A\omega_0}{\rho c} \frac{1}{\sqrt{1+s}}, \tag{51}$$

and this transform is easily inverted to give

$$v(0, t) = -\frac{A\omega_0 U(t)}{\rho c\sqrt{\pi}} \frac{1}{\sqrt{T}} e^{-T}. \tag{52}$$

Thus at $X=0$ the velocity jumps to infinity when the infinite stress impulse is applied, but it does not return immediately to zero when the stress is instantly removed. This condition rather strengthens our view that the stress impulse as a boundary condition leads to a physically reasonable situation. We strike the end of the bar a sharp blow; in so doing we accelerate the end of the bar at once to a very high velocity, and this velocity decays to zero as the energy we have imparted moves along the bar to form the wave.

## SOME COMPUTATIONAL DETAILS

Points on the curve in Figure 1 were obtained by direct evaluation of $v(x, t)$ from equation (25). A short summary of the properties of parabolic cylinder functions is given by Magnus and Oberhettinger (1949), a much longer list of formulas appears in Erdélyi et al. (1953), and Miller (1955) gives an elaborate treatment. For summing the infinite series in (25), we need only the recursion formula,

$$(n+1)D_{-n-2}(z) = -zD_{-n-1}(z) + D_{-n}(z), \tag{53}$$

and the explicit expressions for the first two functions,

$$D_0(z) = e^{-z^2/4}, \tag{54}$$

$$D_{-1}(z) = \sqrt{\frac{\pi}{2}} e^{z^2/4} \operatorname{erfc} \frac{z}{\sqrt{2}}. \tag{55}$$

The last two relations give the first two terms, and the recursion formula thereafter gives each term as a combination of the two preceding terms.

No effort was made to shorten the calculation, since the work was done during what would have otherwise been idle time for a tireless electronic computer. The program was arranged to run until the sum became constant to eight figures. For $X = 4$, this condition required 18 to 28 terms.

## SPHERICAL WAVES

The waves observed in the field experiments of Ricker (1953) and McDonal et al. (1958) correspond to spherical waves rather than plane waves. The Voigt plane waves described by equation (25), and illustrated for $X = 4$ in Figure 1, have only a single lobe. This feature is their most evident departure from the field results. We now consider the previously suggested possibility that spherical waves computed from the Voigt model might show more than one lobe and that this particular difference between the Voigt plane waves and the experimental data might be thus easily resolved.

For spherical waves we consider an infinite solid containing a spherical cavity at whose center we place the origin of the co-ordinate system. The source of the wave is an impulse of pressure (normal stress) applied to the surface of this cavity.

The formulation of this problem is basically more complex than the case of plane waves. Even if spherical symmetry is assumed at the outset, the three normal stress components remain in the equations. It is probably not necessary for us to carry through this part of the analysis. For the case of elastic spherical waves, the details are given by Sharpe (1942). A similar development for spherical Voigt waves is given by Mattice and Lieber (1954).

Two more parameters characteristic of the material appear in the three-dimensional equations, namely Poisson's ratio and a transition frequency for shear waves analogous to the compressional transition frequency $\omega_0$ which we have been using. For our argument we do not require the equations in all their generality. To simplify matters we suppose that the shear-wave transition frequency is equal to the compressional-wave frequency $\omega_0$, and we further select the value one-third for Poisson's ratio to eliminate some numerical coefficients.

With these conditions, we find that the two-sided Laplace transform of $v_r(r, t)$, the particle velocity in a radial direction from the center of the cavity, is

$$_r(r, s)$$

$$= -\frac{A}{\rho c}\frac{a}{r}\frac{\dfrac{as}{c}\left(\dfrac{as}{c}+\dfrac{a}{r}\sqrt{1+\dfrac{s}{\omega_0}}\right)}{\sqrt{1+\dfrac{s}{\omega_0}}\left[\left(\dfrac{as}{c}\right)^2+\dfrac{as}{c}\sqrt{1+\dfrac{s}{\omega_0}}+1+\dfrac{s}{\omega_0}\right]}e^{-\gamma(r-a)}. \qquad (56)$$

The corresponding expression for waves in a purely elastic medium can be obtained by letting $\omega_0$ approach infinity so that $s/\omega_0$ is eliminated wherever it occurs:

$$v_r(r, s) = -\frac{A}{\rho c}\frac{a}{r}\frac{\dfrac{as}{c}\left[\dfrac{as}{c}+\dfrac{a}{r}\right]}{\left(\dfrac{as}{c}\right)^2+\dfrac{as}{c}+1}e^{-s(r-a)/c}. \qquad \text{(elastic)} \qquad (57)$$

The only new symbol in these equations is $a$, the radius of the spherical cavity. The complexity of these expressions, as compared with the plane wave case in equation (17), is due entirely to the spherical geometry.

We now inspect these equations for indications of possible oscillatory behavior leading to wavelets with more than one lobe. We have written the elastic case (57) because here the oscillations are obvious—the quadratic polynomial in the denominator has complex roots which will introduce sines and cosines into the inverse transform. This kind of behavior is shown in detail by Sharpe (1942), who obtained explicit solutions for similar problems.

Comparing the two equations, we argue that the Voigt case could very well turn out to have similar oscillations. We would not expect the transform in (56) to have a simpler inverse than that in (57). Reasoning physically rather than mathematically, we note that the Voigt case (56) includes energy loss or damping—this effect will tend to reduce any initial oscillations as the wave travels out into the solid. The question then is whether these oscillations will be completely damped out in distances involved in the field observations with which we wish to compare them. The answer to this question waits on the inversion of the transform (56), or the more general case with unspecified shear transition frequency and Poisson's ratio which would constitute the complete solution for spherical Voigt waves from a pressure impulse. With sufficient effort, this solution could be worked out.

In this connection we should remark that Mattice and Lieber (1954) carry their analysis (in a different notation) to a point corresponding to (56) and then resort to approximations to evaluate the inversion integral. Unfortunately these approximations are not accurate enough to show the important physical features of the waves, and their results are of no assistance.

## SUMMARY AND CONCLUSIONS

The problem of plane waves in a Voigt solid from a pressure impulse has been formulated in equations (1) to (6), and the general solution for the velocity-type wavelet, valid for all times and distances, is given by equation (25). This equation is suitable for numerical calculation only for fairly small values of time and distance—it was used to compute points on the curve in Figure 1 for the dimensionless distance $X = 4$. The numerical work shows that the velocity wavelet has only one lobe.

An asymptotic solution for very large times and distances is given by equation (32). The method for obtaining additional terms of the asymptotic series is given in the discussion covering equations (37) to (49). This solution is similar to that obtained by Ricker (1943)—the differences result from the use of different boundary conditions or wave sources. Ricker used a doublet impulse of displacement or a triplet impulse of velocity (the first term of Ricker's asymptotic series can also be obtained from a triplet impulse of stress).

The present solution, based on a single impulse of stress, is attenuated more slowly with distance than Ricker's solution. This is a move toward a better match with experimental data, since Van Melle (1954) has shown that Ricker's soltion probably decays too rapidly.

The single-impulse solution has only one lobe, which is a move away from the experimental data. The recent experiments of McDonal et al. (1958), however, suggest that observed wavelets may have only two lobes. An argument based on analogy with the elastic case suggests that if we should calculate *spherical* Voigt waves from a single stress impulse we might find more than one lobe.

The wave shapes which have been computed so far are not enough to reject the Voigt solid as a mathematical model for stress waves in the earth. Ricker's solutions apply only at sufficiently large distances from the source, and the source itself has some undesirable physical properties (a doublet impulse of displacement means that we move the input boundary first to infinity, then to minus infinity, and then back to zero). The general solution (25) describes wavelets from a single stress impulse, an approximation to a physically reasonable source, but these are plane waves and they lack oscillatory properties which might be produced by spherical geometry.

To further test the Voigt model against experiments, we need the complete solution for spherical waves from sources specified in terms of stress (we can start with a single stress impulse as the simplest). Wavelets computed from such solutions may agree with field observations better than any computed wavelets now available.

## ACKNOWLEDGEMENT

This work is a branch of the investigation of the spherical case undertaken

in co-operation with C. C. Lee,[1] who furnished the motivation by using physical reasoning which time and again led to the conclusion that "it must oscillate." Mathematical difficulties with the spherical problem led to a re-examination of the plane wave case with a view to clarifying the method.

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GEOPHYSICS, VOL. XXV, NO. 2 (APRIL, 1960), PP. 505–519, 8 FIGS.

# APPLICATION OF SEISMIC METHODS TO A GROUND-WATER PROBLEM IN NORTHEASTERN OHIO*

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## ABSTRACT

Valleys cut in the bedrock in northeastern Ohio by Tertiary and Pleistocene streams have been filled by Pleistocene glacial drift so that there is little surface evidence of their existence. Some of these buried valleys are good sources of ground water, so information regarding the location, depth, and cross-section of the buried valleys is important in water-supply investigations. Detailed knowledge of the configuration of the buried valleys is useful also in interpreting the glacial history of the region. Test surveys in Portage and Summit Counties, Ohio, by the U. S. Geological Survey indicate that seismic methods can be used to determine depth to bedrock and thus to be applicable to the study of the buried valleys.

## INTRODUCTION

In northeastern Ohio, buried valley systems are often important sources of ground water. These buried valleys had their origin in Pleistocene time when the area was covered by continental glaciation. The effect of glaciation was to reduce generally the relief of the land surface and to fill the pre-existing valleys with glacial drift and lake deposits of highly variable composition and thickness (Winslow, White, and Webber, 1953). There is presently little surface evidence in much of the area that can be used to determine the former courses of the valleys.

In Portage County and part of adjoining Summit County (Figure 1) of northeastern Ohio the thickness of the glacial drift ranges from as little as a few ft to more than 600 ft. The thickest sections are over the buried valleys.

Below the glacial drift, the rocks are essentially horizontal, the formations range in age from Pennsylvanian to Devonian and are predominantly shale except for the Berea and Sharpsville sandstones of Mississippian age and the Sharon conglomerate member of the Pottsville formation of Pennsylvanian age (Figure 2).

Some of the buried valleys are good sources of ground water, but others are not, depending principally upon the composition of the valley fill and upon the recharge rate from surface water or the adjacent bedrock. When the streams that formed the buried valleys flowed to the south, away from the glaciers, they carried large amounts of glacial outwash; the coarser sand and gravels were deposited near the ice front, providing a permeable fill that is very favorable to the development of excellent ground-water supplies. The streams flowing to the north were dammed by the advancing ice and fine-grained sediments were deposited in the resulting lakes. These fine-grained sediments are relatively im-

* Publication authorized by the Director, U. S. Geological Survey. Manuscript received by the Editor June 24, 1959.

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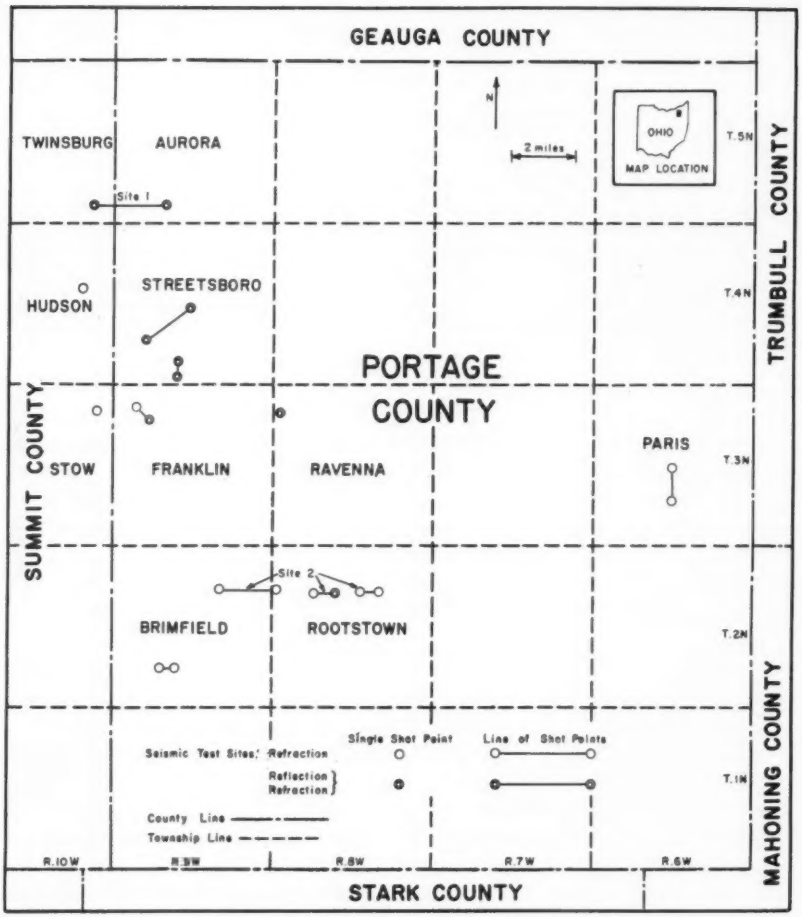


FIG. 1. Outline map of Portage County and surroundings showing the locations where seismic work was done.

permeable and generally are poor areas for the development of ground-water resources.

In geologic studies related to water supply problems it is therefore important to investigate the buried valleys. In some places there is sufficient geologic control in the form of bedrock exposures and the records of wells to permit the construction of a contour map of the bedrock surface. When such control is lacking, depth-to-bedrock measurements by geophysical means can provide valuable information.

| Age | Group, formation, or member | | Lithology | Thickness in feet |
|---|---|---|---|---|
| Pennsylvanian | Sharon conglomerate, member of the Pottsville formation | | Conglomerate and sandstone | 60 - 100 |
| Mississippian | Cuyahoga Group | Meadville shale | Shale | 30 - 50 |
| | | Sharpsville sandstone | Sandstone | 10 - 30 |
| | | Orangeville shale | Shale | 70 - 80 |
| | Berea sandstone | | Sandstone | 30 - 40 |
| | Bedford shale | | Shale | 40 - 75 |
| Devonian | Ohio shale (Cleveland member) | | Shale | 30 |
| | Chagrin shale | | Shale | 600 |

FIG. 2. Generalized geologic section of the consolidated rocks cut by valleys now buried beneath the glacial drift in Portage County, Ohio.

In addition to the direct economic value of locating possible sources of ground water, detailed information of the configuration of the buried valleys is helpful in interpreting the glacial history of the region and in determining the direction of flow of the preglacial streams. Seismic methods for these purposes were tested in Portage and Summit Counties, Ohio, in the late summer of 1954, by the U. S. Geological Survey in co-operation with the Ohio Department of Natural Resources, Division of Water. The early results were so promising that more extensive field work was undertaken in the summer of 1955. Some of the results of the initial seismic work in this area have been presented previously (Pakiser and Warrick, 1956).

## FIELD WORK

The initial experimental seismic measurements were made near a borehole in Aurora Township, Portage County, Ohio, that went deep into the bedrock and revealed a thick section of glacial drift overlying the bedrock. When it was found that reflections could be recorded that corresponded with the known depth-to-bedrock, a seismic profile of this buried valley was made with a series of reflection and refraction recordings. Later a series of depth-to-bedrock determina-

tions were made in areas selected from the geologic data that Winslow had collected in the water-resources study of the region (Winslow and White, written communication, 1959). Sites for seismic tests were selected with the objective of completing a bedrock-contour map of Portage County. At many places the glacial drift covered the bedrock to a thickness sufficient for water wells to be completed within the drift, so that the bedrock was known only to be deeper than the wells. It was in these areas lacking outcrop or well-boring control that the seismic tests were made. A total of six weeks was spent in field work. The test sites are shown on the outline map of Portage County, Ohio, and surroundings (Figure 1).

## EQUIPMENT AND PROCEDURES

The equipment used in the seismic work included 12 amplifiers and a recording oscillograph especially designed to handle signal frequencies of 75 to 300 cps. These frequencies are higher than those used in conventional reflection work, because the higher frequencies have been found to be better suited for use in shallow investigations. The use of higher frequencies permits better resolution of the reflected events and largely eliminates the interference from surface waves. The same amplifiers permitted signals as low as 5 cps to be recorded so that conventional refraction work also was possible. The seismometers used to convert the seismic energy into electrical energy were of the electromagnetic type. Seismometers with a natural frequency of 40 cps were used in the reflection work and seismometers with a natural frequency of $7\frac{1}{2}$ cps were used in the refraction work. A detailed description of these instruments has been published (Pakiser, Mabey, and Warrick, 1954). The recording system was enclosed in a cab mounted on a small truck. The cab served also as a darkroom for processing the records. A small truck-mounted rotary drill, a water truck, and a shooting truck completed the equipment used in the field work.

After the initial tests had shown the practicality of seismic methods for depth-to-bedrock measurements, a field procedure was devised. First a refraction profile of sufficient length to detect bedrock, should it exist within 300 ft of the surface, was run as a reconnaissance method. When a place was found where no indications of the bedrock velocity appeared on the refraction record, reflection methods were used.

High explosives were used as the seismic energy source for both refraction and reflection recordings. Except for a few experiments with air shooting, the explosives were placed in a shot hole drilled to a depth of 15 to 30 ft so as to be below the near-surface low-velocity layer. Reflection records required very small explosive charges. Often a single No. 6 electric blasting cap provided sufficient energy, but some areas required the use of a seismograph booster (a small RDX charge) with a cap. Refraction records required more energy, so one pound of either 50 percent ammonium nitrate dynamite or nitro carbo nitrate was commonly used.

At shot point Tw 2, in Twinsburg Township, Summit County, comparisons of charges fired in the air to charges fired in a fluid-filled shot hole were made. This location was chosen because it was distant from dwellings. The seismometers were arranged in an inline split-spread about the shot hole Tw 2 for the hole shots. The air shots were recorded using the same seismometer array, but the charge was placed 300 ft west of the westernmost seismometer. This offset was necessary to permit the desired reflections to be recorded prior to the air wave. The air shots usually yielded one clear reflection at a time approximating the bedrock reflection time. In the selected records of Figure 3, the corrected reflection time for the air shot is somewhere between the alternatives for the bedrock reflection on the hole-shot record. The depth points for the two records are not identical because of the different offsets involved, so that exact reflection-time comparisons are not valid. Both records were made using a filter band-pass of 75 to 300 cps, and identical pre-suppression time constant. The amplifier gain for the air shot was approximately twice the gain used for the hole shot. A single No. 6 electric blasting cap placed at a depth of 17 ft in the shot hole provided the energy for the hole shot. A two-ounce charge of 50 percent dynamite primed with a No. 6 cap and set 5 ft above the surface of the ground was the energy source for the air shot. From the tests of the air shots it was decided that, while satisfactory bedrock-depth information might be obtainable by their use, the rather dense population of much of the area would introduce complications that should be avoided.

The refraction records were obtained by using a spacing of 100 ft between seismometers in an inline arrangement with a distance of from 50 to 300 ft between the near seismometer and the shot hole. Reflection spreads of both the inline and a split-inline arrangement of seismometers were used. The distance between seismometers was 25 ft and the distance between the shot hole and the nearest seismometer ranged from 25 to 100 ft. Only one seismometer for each record trace was used.

The seismic recordings were converted to depths through the use of conventional computing methods (Dix, 1952, ch. 6 and 8). Reflection depths were computed from the time between the shot instant and the arrival of the reflected event. This reflection time was corrected for the low-velocity layer by use of the uphole time, and then further corrected to a reference elevation. The corrected reflection time was converted to depth by use of a velocity assumed to exist between the reference elevation and the reflecting horizon. Velocities used in the computations were derived from refraction profiles.

The depths were derived from refraction records by use of the conventional time-intercept method (Dix, 1952, ch. 12). At most places the dip of the refraction horizon was so slight that depths computed with the assumption that the refracting horizons were horizontal were sufficiently accurate (Nettleton, 1940, p. 269).

Depths determined by the seismic methods were calculated to the ft as a

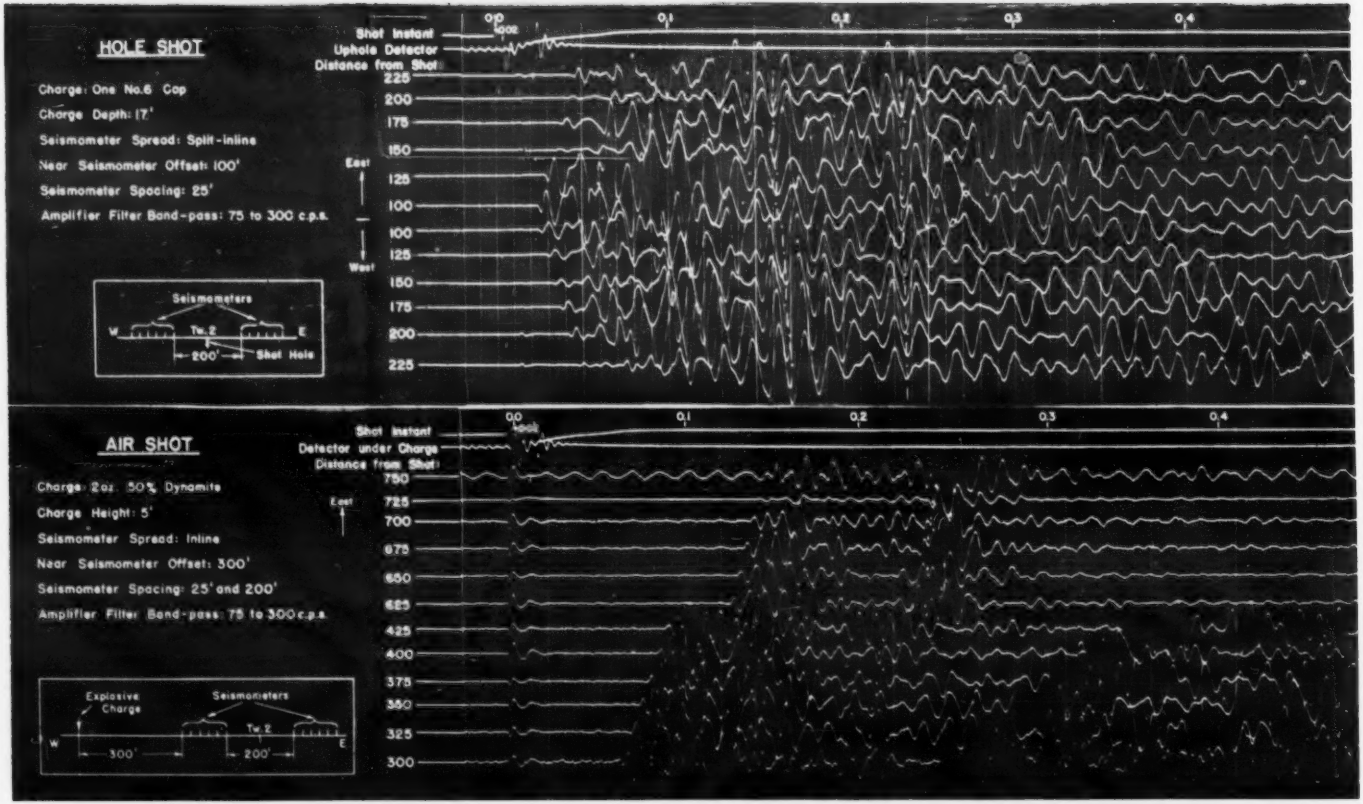


FIG. 3. Comparison of air shots and hole shots in reflection records near Tw 2, Summit County, Ohio.

matter of convenience and are not represented as being correct to the nearest ft. No vertical velocity surveys were made, so that the velocities assumed for reflection computations may be somewhat in error. The velocities used were determined from refraction data and where possible from correlation of the reflection signal with the known distance to- bedrock at borehole locations. If the elevations determined for the bedrock surface are correct to within 20 percent, the purposes of this work are satisfied. The relative elevations determined for adjacent shotpoints should be expected to have an accuracy greater than the accuracy in absolute depth determinations.

## RESULTS

As a result of the seismic work, many areas where geologic control was lacking were eliminated as possible buried-valley locations with a few refraction profiles. Existence of buried valleys was confirmed at several locations and their depths were determined. The depth measurements aided in the determination of the direction of streamflow in the valleys prior to their filling with glacial drift and helped determine which of the buried valleys contained the major streams, and which were the tributaries. The seismic depth determinations provided a basis for the development of theories regarding the buried valleys and their relation to the glaciation of the area. For example, the deep buried valley crossed by the profile extending from Twinsburg Township of Summit County into Aurora Township of Portage County was believed earlier (Winslow, White and Webber, 1953) to be principally part of the Yarmouth (interglacial stage) drainage system which was partially filled with outwash from the Illinoian ice stage of glaciation. The seismic investigations of the buried-valley systems in Portage County show that this valley is much more complex and that it was probably developed initially in Teays (preglacial) time. It now appears that the valley bottom in Teays time was cut to an altitude of about 700 ft above sea level. This valley appears to have been tributary to a major stream which flowed generally northward from Stark County to a point near Ravenna, Portage County, then eastward to what is now the Grand River Lowland, and then presumably northward, eventually joining the Lake Erie basin (Figure 4).

The courses of the major buried valleys shown in Figure 4 were determined mainly from geologic data. The seismic bedrock-depth determinations helped establish the position of the buried valleys with greater precision at some localities and gave evidence regarding the direction of flow of the streams that once occupied the valleys, as well as indicating which valleys were tributaries to the main valleys.

Two of the ten sites of seismic work will be described in some detail. Site 1 in Twinsburg and Aurora Townships was studied chiefly with the reflection method, and Site 2 in Brimfield and Rootstown Townships is an example of the use of the refraction method.

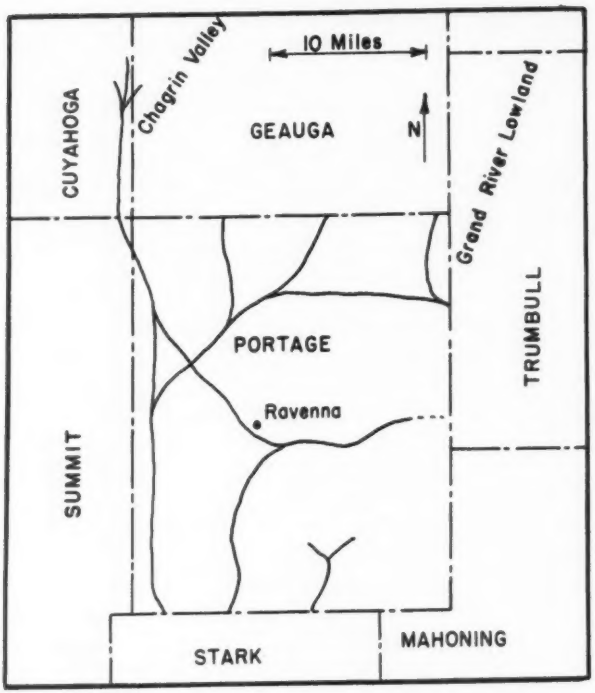


FIG. 4. Outline map of Portage County and surroundings showing the course of the major buried valleys related to this study.

*Site 1, Example of a reflection seismic test*

The first tests of the reflection method in Portage County, Ohio, were conducted in southwestern Aurora Township at Site 1 (Figure 1). The buried valley is indicated in this locality by a linear north-south topographic depression about two miles wide and 100 to 200 ft lower than the surface at either side. A deep borehole proved the existence of this buried valley and provided a control point for the seismic tests. The depression was formed, in large part, by differential compaction of the glacial drift, the thick section of the drift in the buried valley having settled more than the thin mantle of drift over the bedrock at the valley sides. The Sharpsville and Berea sandstones form benches along modern valleys in the area, and may be presumed to have formed benches along the sides of the buried valleys. In the vicinity of southwestern Aurora Township, the Sharpsville sandstone is between 10 and 30 ft thick and its top surface can be expected at an altitude of about 950 ft. The Berea sandstone is 30 to 40 ft thick in the area of Site 1 and its bench should occur at an altitude of about 800 ft. The surface altitude at this location averages about 980 ft.

Initial reflection tests near the control boring yielded records containing several reflection events. In addition to the one that correlated with the bedrock depth at the borehole, several reflections were observed to occur within the Pleistocene section. Several seismometer spreads were arranged and shot from each end to make a closely spaced subsurface section to check on the continuity of the reflections. As expected, owing to the discontinuous nature of the material within the Pleistocene section, several of the reflection events were not continuous. Figure 5 illustrates the detailed portion of Site 1 and shows the variability of the reflections in the Pleistocene section. The vertical scale is time—the time it would take for the seismic energy to travel from the datum or the reference elevation to the reflecting horizon and return. The log of the borehole used for control, furnished by the Wheeling and Lake Erie Railroad, has been put on the time scale by assuming a velocity of 5,500 ft/sec from the datum elevation of 950 ft to the bedrock. The most continuous reflections seem to occur at about 0.076, 0.125, and 0.200 sec, and are connected by dashed lines on the figure. The 0.076 reflection is near a change from a mixed sand-gravel-clay zone to a uniform clay zone. The reflection at about 0.125 matches approximately with a change from the gravel to the sandy clay zone in the borehole log. The bedrock is represented by the 0.200 reflection.

The letters in the shotpoint designation refer to the township in which the shotpoint is located. At the left side of the log on Figure 5, the reflection times for a seismometer spread to the north of point Au 1 are plotted. The borehole is 160 ft north of the Au 1 shotpoint, so the subsurface coverage of the seismometer spread to the north of Au 1 corresponds to the borehole location better than the subsurface coverage of the spread to the east of Au 1. The reflection events plotted for Au 1 North seem to match with the lithologic changes better than the events for Au 1 East. The shotpoint Tw 1, in Twinsburg Township, Summit County, on the left side of Figure 5 is included in this section to illustrate two of the alternatives possible in the selection of the reflection corresponding to the bedrock. At Tw 1, the poor reflection at about 0.170 sec permits a somewhat simpler profile for the buried valley; however, the 0.227 sec reflection is preferred as the bedrock reflection because it is of a much higher grade, corresponding in quality to the reflections representing bedrock at the shotpoints to the east.

The entire profile at Site 1 from which Figure 5 was taken is shown in Figure 6. The elevation point of 662 ft to the east of Tw 3 represents the maximum possible altitude of the bedrock at that point because at Tw 3 the refraction method was used and no bedrock velocity was recorded with the seismometer spread that was used so only a minimum depth could be estimated. The actual bedrock location at that position is at some altitude below 662 ft. Two possible choices of bedrock position west of Au 1 are shown by the two dashed lines. In one, the maximum depth of the valley is 662 ft at Au 2. In the other, which is preferred because the reflection has character similar to bedrock reflections from adjacent spreads, the maximum depth of the valley is 726 ft at Tw 1. The bedrock posi-

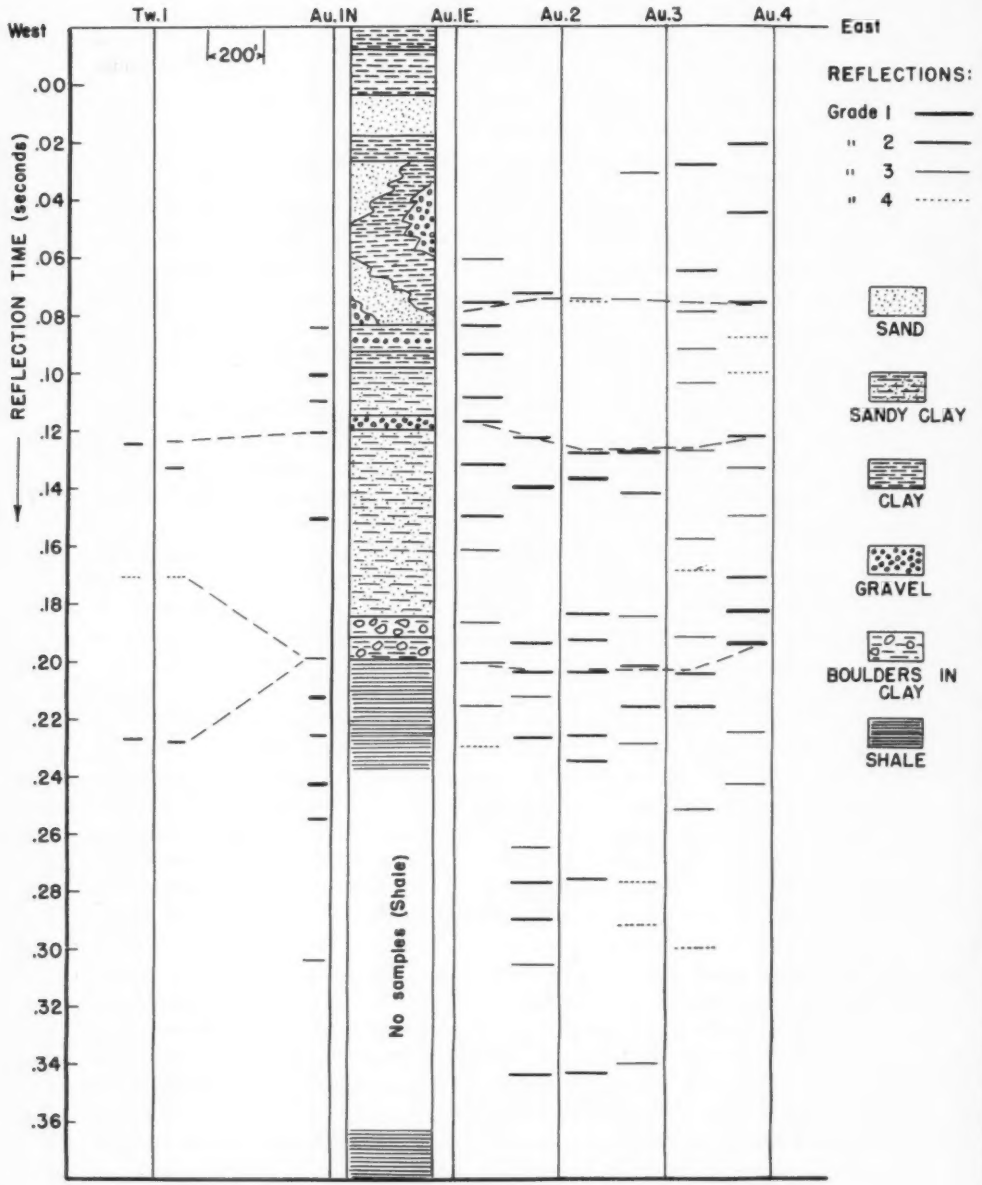


FIG. 5. Seismic reflection time section for a portion of Site 1, Aurora Township, Portage County, Ohio, including the geologic log of the control boring.

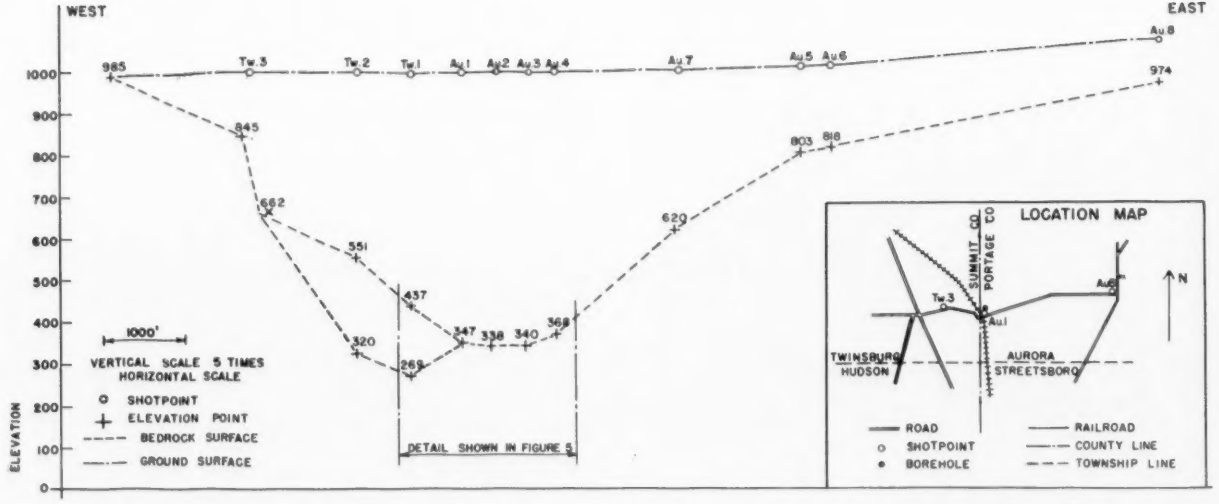


FIG. 6. Seismic profile across the buried valley at Site 1, Portage and Summit Counties, Ohio, including the portion shown in Figure 5.

tion at Tw 3 and Au 8 at the ends of the profile were determined by the refraction method. Bedrock crops out in a stream bed about 1,650 ft west of Tw 3.

The abrupt change in slope between Tw 3 and Tw 2, and to a lesser extent between Au 7 and Au 5, is probably caused by a ledge of the more resistant Berea sandstone on the valley wall. The Berea sandstone was expected to be at an altitude of about 800 ft, and the change in slope as determined from the seismic data occurs somewhere between the altitudes of 662 and 845 ft on the west flank of the valley and between 620 and 803 on the east flank of the valley. No detailed seismic profiles were run across these sections of the major profile so a more precise altitude of the ledge cannot be given from the seismic data.

The buried valley crossed by this profile at Site 1 is believed to be a tributary that drained parts of Cuyahoga, Geauga, Portage, and Summit Counties which flowed generally south to southeastward and joined the Teays age river near Ravenna (Figure 4).

This valley where crossed by the seismic profile at Site 1 is 200 ft or more lower than buried-valley bottoms elsewhere in the area. It is concluded that the depression in the bedrock surface is the result of ice erosion which occurred when a tongue or lobe of ice pushed southward, up what is presently the Chagrin Valley, and eroded the valley bottom to an altitude of about 300 ft in northwestern Portage County during either the Nebraskan or Kansan glacial stage.

*Site 2, Example of a refraction profile*

The refraction line selected for detailed discussion is the collection of east-west line segments shown as Site 2 in northeastern Brimfield and north-central Rootstown Townships in Figure 1. At this location refraction profiles were made in reconnaissance for the buried valleys. The overall length of the line totals a little more than $5\frac{1}{2}$ miles and contains 18 shotpoints (Figure 7). The upper portion of Figure 7 (Figure 7a) represents the entire profile of Site 2 and shows the altitude of the surface of the ground and of the bedrock surface. Here the Sharon conglomerate member of the Pottsville formation is about 100 ft thick and forms the bedrock surface along most of the line of profile between altitudes of about 900 ft and 1,000 ft above sea level. The Berea sandstone is about 50 ft thick and lies between 710 ft and 760 ft above sea level. The bedrock surface is fairly even except for the small buried valley shown between Ro 8 and Ro 3. This buried valley has a probable maximum relief of 220 ft if measured from the 1,000-ft altitude. The western portion of this valley is shown in greater detail in the lower part of Figure 7 (Figure 7b). The velocities observed along this part of the line were reasonably consistent. The average velocity in the zone within 20 ft of the surface, as computed from the uphole times and the charge depths, was 2,000 ft/sec with a maximum variation of 20 percent. The average velocity in the Pleistocene glacial drift below the low-velocity zone was 5,700 ft/sec and the maximum variation was seven percent. The average velocity in the bedrock was 11,300 ft/sec with a maximum variation of ten percent. Higher bedrock veloci-

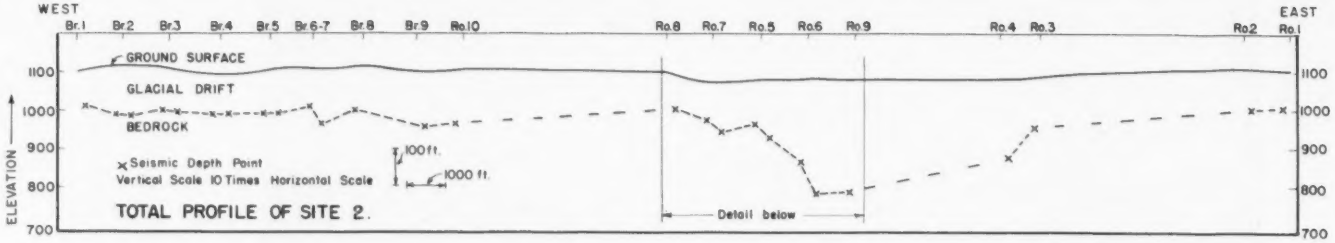


FIG. 7a. Bedrock profile as derived from refraction data at Site 2, Brimfield and Rootstown Townships, Portage County, Ohio.

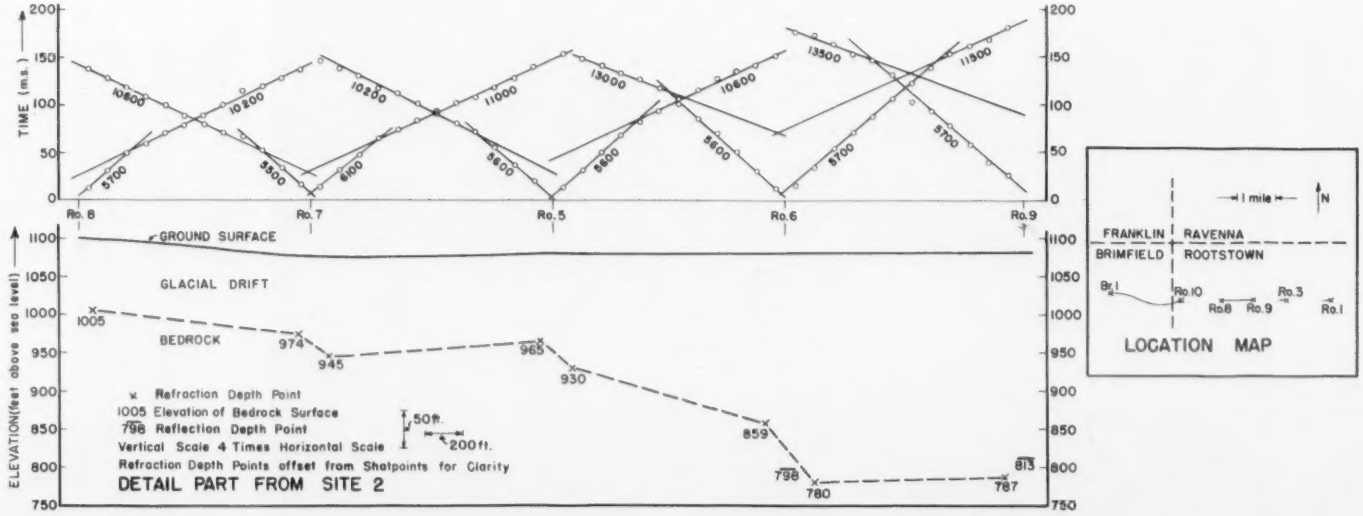


FIG. 7b. Portion of 7a on a larger scale including refraction time-distance curves and corresponding bedrock profile, and reflection check points.

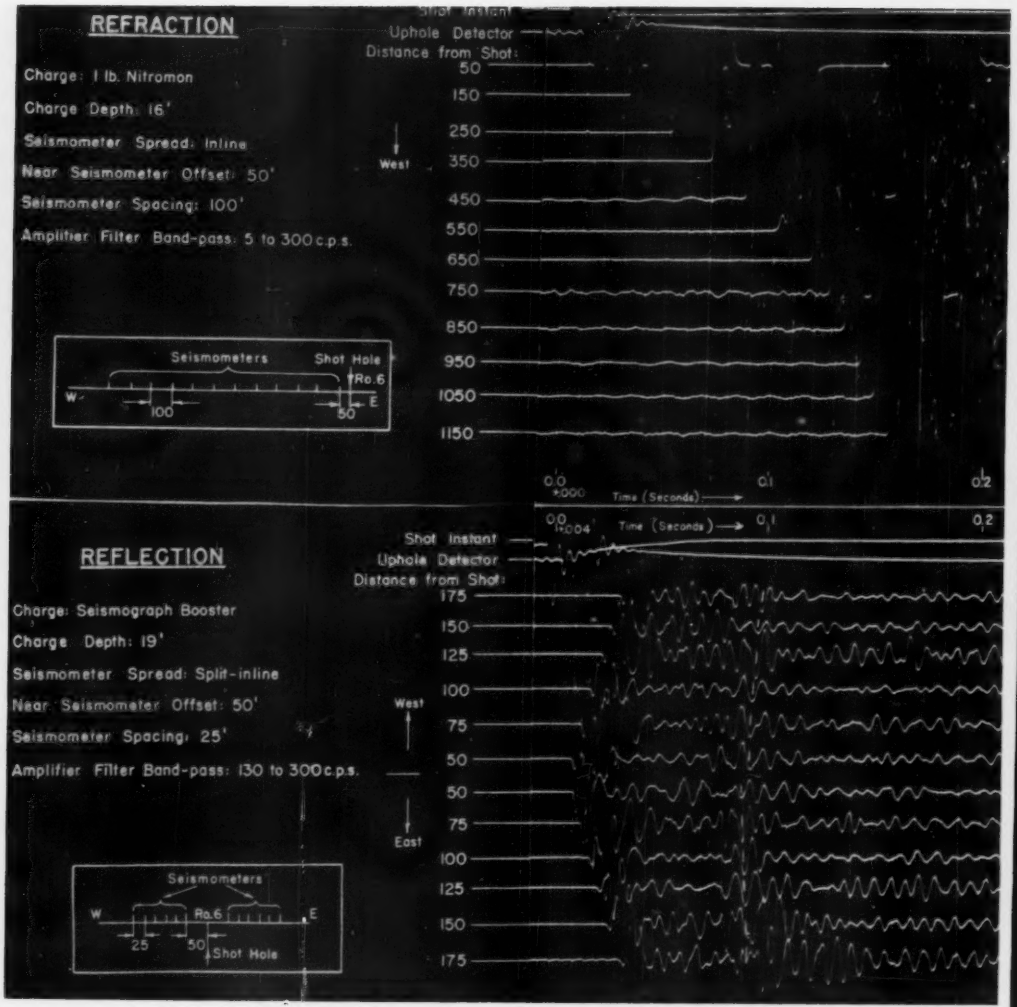


FIG. 8. Selected refraction and reflection records at location Ro 6 of Site 2, Rootstown Township, Portage County, Ohio.

ties in the deeper parts of the valley may indicate a change in the nature of the bedrock.

At Ro 6 and Ro 9 reflection records were made to provide a check with the refraction data. At Ro 6 the elevation determined by the reflection methods lies

between the elevations determined by the refraction method with seismometer spreads at either side of the shotpoint. At Ro 9 the reflection elevation is 26 ft higher than the nearest refraction elevation. The reflection derived elevations check fairly well with refraction results and provide some evidence in support of the belief that the valley bottom rises to the east of Ro 6.

Illustrations of both refraction and reflection records at Ro 6 are shown in Figure 8. The reflection records at this location are relatively free of reflection events corresponding to horizons within the Pleistocene section so that the bedrock reflection is more prominent.

## CONCLUSIONS

The examples given for Sites 1 and 2 are typical of the methods used and the results obtained at the other seismic test sites. The seismic work has provided much needed information on the depth of the buried valleys as well as to the shape of the valley bottoms. This information is of direct value in outlining possible sources of ground water and for providing evidence useful in interpreting the glacial history of the region.

## ACKNOWLEDGMENTS

The authors are indebted to L. C. Pakiser, who first interpreted the seismic results of the field work done in September of 1954, a portion of which is included in Figures 5 and 6 to the east of the control borehole. M. F. Kane and D. G. Murrey assisted the authors in the 1954 field work and J. W. Berg, Jr., R. K. Cash, J. G. Knoche, and D. G. Murrey assisted in the 1955 field work.

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Nettleton, L. L., 1940, Geophysical prospecting for oil: New York, McGraw-Hill Book Co.

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Pakiser, L. C. and Warrick, R. E., 1956, A preliminary evaluation of the shallow reflection seismograph: Geophysics, v. 21, no. 2, p. 388–405.

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# EDITORIAL

The Editor cannot begin this term of office without expressing a very deep gratitude to his predecessor, Dr. Lawrence Y. Faust, for two things. The first of these is the excellency of his office. Secondly is the abundance of thought and work exercised by Dr. Faust to make the transition from his term as easy a burden on the new Editor as this could possibly be.

One can only hope to emulate the previous two years. To make this possible, this Editor has been privileged to have an editorial board of men who are each experts in his particular field. Moreover, each is dedicated to his particular role in making GEOPHYSICS a fine journal from a technical standpoint and a very readable journal from the standpoint of the membership. Rest assured that editorial policies and decisions will reflect the opinions of this group and not simply those of the Editor because there is little point in having this advisory group without drawing liberally upon its services.

Dr. L. L. Nettleton is the Assistant Editor. This is fortunate from a practical standpoint because he shares the same office address with the Editor and can act for the Editor during his absence. Moreover, you will recall that Dr. Nettleton was formerly both Editor and President of the Society, so having his experience at first hand is really a privilege. Some of Dr. Faust's Associate Editors have been kind enough to continue. In particular, Mr. E. J. Stulken in Seismic Field Techniques and Operations, Mr. G. E. Archie in Well Logging, and Dr. O. F. Ritzmann in Patents. Newly appointed Associate Editors are Dr. Arthur Brant in Mining Geophysics, Dr. Norman Paterson in Magnetics, Dr. R. J. Bean in Gravity, Dr. F. A. Van Melle in Seismic Theory and Experimental Seismology, and Dr. Robert Jastrow in Space Physics.

This last subject group, Space Physics, is newly introduced in order to try to develop interest in the application of geophysical techniques to space exploration. Currently, extensions of the earth's magnetic and gravitational field into space are very actively under survey with results that are somewhat pertinent to the exploration field and with techniques that are certainly of great interest to us. Moreover, many of us have been approached by governmental agencies in respect to the adaptation of our exploration techniques to the rather startling new thought of exploration of planets themselves. We would like to see this small but highly interesting area of interrelationships between earth exploration and space exploration brought into our journal during the next two years, and Dr. Jastrow's appointment is the first step in this direction.

Mining geophysics is expanding greatly, and its relative expansion within our organization is accentuated by the fact that petroleum geophysics is perhaps not expanding at this time at all. Excellent mining sessions have been featured at recent annual meetings, and it is hoped that some of the better papers will be submitted for publication in GEOPHYSICS. The Editor feels that GEOPHYSICS has a chance to make a distinct contribution in this area by publishing articles

which show quantitatively the relationship between the geophysical anomalies and the actual physical conditions. Out of a series of these may eventually develop dependable physical constants of the various rock types, parameters which are most essential to quantitative interpretation.

The membership should very earnestly consider that GEOPHYSICS can only endure if the really interesting and significant things that the members do are reported by publication in GEOPHYSICS. For example, many of you have discussed with Dr. Faust and myself the absence of Case Histories which are perhaps the most avidly read articles. The fact that there have been few of these is readily acknowledged, but the fact that the responsibility for their appearance lies, first, with the membership is not so often acknowledged by the members. So may we close with this plea to the membership to support GEOPHYSICS by submitting manuscripts for possible publication.

The Editor

# DEPARTMENTS

## PATENTS

O. F. Ritzmann†

### ELECTRICAL PROSPECTING

*U. S. No. 2,903,642.* H. O. Seigel. Iss. 9/8/59. App. 6/23/55. Assign. Rio Canadian Exploration Ltd.

*Method of Mobile Electromagnetic Prospecting.* An airborne electromagnetic prospecting system using two similarly oriented transmitting coils excited at different frequencies so that the fields are affected differently by conducting ore bodies, and two orthogonal receiving coils whose emf's are measured and combined so that the direction of the resultant field vector can be determined at the two frequencies and compared.

*U. S. No. 2,908,863.* R. J. Neff. Iss. 10/13/59. App. 2/18/55.

*Electronic Locator.* A device for locating non-metallic buried pipe having an antenna system that is inserted in the pipe on a flexible cable and energized by a transmitter on the surface, the antenna being shielded so that it does not radiate along the axis of the pipe and rotated by means of the cable, and located by means of a search receiver on the surface.

### GRAVIMETRIC PROSPECTING

*U. S. No. 2,907,211.* J. B. Breazeale, C. G. McIlwraith, and E. N. Dacus. Iss. 10/6/59. App. 9/6/57. Assign. Bill Jack Scientific Instrument Co.

*Gravity Meter.* A gravity meter having an unbalanced disk in a magnetic suspension allowing rotation about the axis of the disk with quartz fiber control and a servo system to return the system to a null position.

### MAGNETIC PROSPECTING

*U. S. No. 2,902,636.* F. B. Coker and O. W. Schoenberg. Iss. 9/1/59. App. 11/12/53. Assign. United Geophysical Corp.

*Recording System.* A recording system for a truck-borne magnetometer in which the recording medium may be driven either by a clock or by the truck wheels and the magnetometer reading is recorded either at intervals of time, distance, or when desired by the operator, and with the record including the orientation of the truck so that correction can be made for its disturbing field.

*U. S. No. 2,902,641.* W. E. Fromm. Iss. 9/1/59. App. 7/22/55. Assign. U.S.A.

*Method of Orientation of Detector Magnetometer Element with High Accuracy.* A method of adjusting the detecting element of a magnetically stabilized magnetometer so that it is perpendicular to the plane of the orienting elements by applying a deflecting field by means of a transversely oriented current-carrying coil and adjusting the magnetometer so that it reads the same when the current in the coil is reversed.

*U. S. No. 2,906,929.* R. D. Wyckoff. Iss. 9/29/59. App. 5/28/54. Assign. Gulf Research & Development Co.

*Temperature Compensated Permanent Magnet.* A temperature-compensated permanent-magnet structure combining magnetically opposed magnets of different magnetic moment and of different

† Gulf Oil Corporation, Patent Department.

temperature coefficient so as to attain an overall temperature coefficient of zero or other desired value.

RADIOACTIVITY PROSPECTING

*U. S. No. 2,904,691.* R. P. Mulligan. Iss. 9/15/59. App. 6/4/54. Assign. Texaco Inc.

*Aerial Prospecting.* An airborne radioactivity prospecting system using a self-propelled aircraft towing one or more gliders carrying radioactivity detectors and arranged to survey at different heights or on laterally spaced flight lines.

*U. S. No. 2,906,882.* J. W. Merritt. Iss. 9/29/59. App. 10/25/56.

*Radiation Survey Method.* A gamma-ray prospecting method in which the gamma-ray activity is measured, and soil samples are taken and retentivity characteristics of the soil measured so that the gamma-ray measurements can be corrected for variations in soil characteristics.

*U. S. No. 2,908,839.* G. Herzog. Iss. 10/13/59. App. 6/15/53. Assign. Texaco Inc.

*Radiation Detector Cathode.* A multi-plate cathode type of radiation detector in which the plates are made of fine wire mesh with the mesh wires of each cathode soldered together in a ring around the hole through which the anode wire passes.

*U. S. No. 2,910,592.* F. C. Armistead. Iss. 10/27/59. App. 9/9/53. Assign. Texaco Development Corp.

*Scintillation Type Detector.* A scintillation type radioactivity detector having alternate layers of fast-acting and of slow-acting luminophors with thin sheets of neutron-reactive material between them so that neutrons will produce scintillation in both luminophors whereas gamma rays will produce scintillations in but one of the luminophors, the photo-multiplier tube being connected to circuits that indicate coincident and non-coincident scintillations.

SEISMIC PROSPECTING

*U. S. No. 2,902,106.* C. H. Carlisle and T. Flatow. Iss. 9/1/59. App. 12/8/55. Assign. Jersey Production Research Co.

*Method of Determining the Dip of Geologic Formations in the Vicinity of a Borehole.* A method of well shooting in which an interval-velocity log is first run and a shot then placed in the well at the top of a high-velocity layer, and refraction records made along a radial line extending away from the well.

*U. S. No. 2,902,107.* L. W. Erath and P. E. Madeley. Iss. 9/1/59. App. 3/13/56. Assign. Dresser Industries, Inc.

*Method and Apparatus for Compositing Seismic Exploration Results.* A method of compositing magnetic records taken with successive shots to the same geophone by magnetically recording the shots and adding their signals on playback in proper proportion to maintain proper modulation on magnetic rerecording.

*U. S. No. 2,902,627.* J. L. Colten. Iss. 9/1/59. App. 3/30/55. Assign. Gulf Research & Development Co.

*Seismograph Shot Firing Device.* A seismograph shot-firing device having a manually driven generator which charges a pair of condensers in parallel and at the end of the generator stroke simultaneously discharges one of the condensers through the cap and the other through the time-break circuit.

*U. S. No. 2,902,667.* W. W. Schriever. Iss. 9/1/59. App. 10/21/54. Assign. Jersey Production Research Co.

*Vertical Velocity Dynamic Geophone.* An annular geophone that may be slipped over a cable and having two annular magnets with a coil suspended in a radial air gap by means of cantilever springs parallel to the axis so that movement of the coil transverse to the axis generates an emf due to asymmetry of the coil and magnet.

*U. S. No. 2,902,668.* C. H. Savit. Iss. 9/1/59. App. 5/28/56. Assign. Western Geophysical Company of America.

*Pressure Sensitive Device.* A variable air-gap reluctance type hydrophone in which the magnet pole pieces are carried in a non-magnetic electrically insulating plate whose surface conforms to the maximum elastic deformation of the diaphragm so that the excessive pressures cannot damage the diaphragm.

*U. S. No. 2,903,969.* F. F. Kolbe. Iss. 9/15/59. App. 5/28/53. Assign. The Maumee Collieries Co.

*Method of Blasting.* A method of loading a shot hole by placing a flexible liner in the hole and introducing a granular solid explosive such as ammonium nitrate and subsequently introducing through a tube to the top of the granular charge a liquid component such as kerosene to expand the liner into contact with the hole.

*U. S. No. 2,904,681.* J. L. Jones, Jr. and L. D. Anderson. Iss. 9/15/59. App. 9/15/54.

*Feedback Amplifier for Extending the Useful Frequency Range of an Accelerometer.* An accelerometer having a strain-gauge type of transducer connected to an amplifier having a feedback loop with an analog circuit whose response corrects the variation in frequency response of the mechanical system.

*U. S. No. 2,905,772.* T. Bardeen. Iss. 9/22/59. App. 11/14/55. Assign. Gulf Research & Development Co.

*Automatic Volume Control Systems for Seismograph Amplifiers.* A seismograph amplifier system having saturable-core reactors with common d-c control so that a single control adjusts all filters, and also having a long time-constant common avc with the avc bridges balanced to ground, and short time-constant individual avc's acting on a single stage, and limiters to prevent blocking in each channel.

*U. S. No. 2,906,198.* J. A. Westphal. Iss. 9/29/59. App. 1/16/58. Assign. Sinclair Oil & Gas Co.

*Numbering Device for Timing Lines on a Seismogram.* A device for counting and numbering timing lines on a seismogram having a photoelectric counter controlling a relay and printer that stamps the number on the seismogram as it is passed through the device.

*U. S. No. 2,906,363.* C. S. Clay, Jr. Iss. 9/29/59. App. 5/6/55. Assign. Jersey Production Research Co.

*Multiple Transducer Array.* A geophone array that rejects horizontally traveling waves by using sets of uniformly spaced geophones arranged with non-uniform spacing between sets so that the overall array will have cancellation characteristics for a broad band of horizontal wave lengths.

*U. S. No. 2,906,992.* K. H. Wilcoxon. Iss. 9/29/59. App. 5/23/57. Assign. U.S.A.

*Towed Hydrophone.* A hydrophone connected to its towing cable by an elastic sleeve through which the electrical cable passes and enclosed in an ellipsoidal housing whose center section is perforated to permit entrance of water and water-borne vibrations.

*U. S. No. 2,906,993.* R. L. Steinberger. Iss. 9/29/59. App. 5/22/46.

*Transducer for Underwater Sound.* A piezoelectric hydrophone having behind the backing plate an air cell surrounded by oil that is in pressure equilibrium with the ambient fluid and also having oil in pressure equilibrium in front of the piezoelectric crystals.

*U. S. No. 2,906,994.* M. J. Pellillo. Iss. 9/29/59. App. 3/22/55.

*Seismometers.* A seismometer having a spring-supported mass on the end of a bar whose other end has a frustoconical flange that acts as a fulcrum and carries an armature that varies the air gap of a reluctance transducer or carries a coil in an annular magnetic field, the entire structure being axially symmetrical so that it will operate in any orientation about the longitudinal axis.

*U. S. No. 2,906,995.* A. A. Chernosky. Iss. 9/29/59. App. 11/14/56. Assign. Jersey Production Research Co.

*Variable Gap Reluctance Transducer.* A seismometer having a pair of semi-cylindrically shaped magnets spaced at four corners by omega-shaped springs, the magnets being wound with pick-up coils and made of permanently magnetizable material having high reversible permeabillty such as Permendur.

*U. S. No. 2,907,012.* D. Pitman, D. F. Rutland, and G. J. Giel. Iss. 9/29/59. App. 12/30/55. Assign. U.S.A.

*Sofar Alarm.* An underwater acoustic alarm system that is tripped by wave energy above the background noise and having a full-wave rectifier and differentiator of long time constant whose output successively trips a pair of trigger circuits whose time delay is longer than noise peaks but shorter than signals to be indicated.

*U. S. Re. 24,709. (Original No. 2,781,502).* D. C. Richards. Iss. 10/6/59. App. 3/18/54, 2/12/57, and 10/22/57. Assign. Socony Mobil Oil Co., Inc.

*Self-Orienting Geophone.* A vertical seismometer that is insensitive to orientation about a horizontal axis and having a permanent magnet system rotatably mounted on a horizontal axis so that gravity will maintain its vertical orientation and having a coil mounted on an axially symmetrical cantilever spring so as to vibrate in a vertical plane close to the end of the magnet.

*U. S. No. 2,907,400.* T. W. Swafford, Jr. Iss. 10/6/59. App. 5/12/54. Assign. The Geotechnical Corp.

*Correlation of Seismic Signals.* A correlation-type time domain filter in which the seismic signal is divided and one part delayed in time, both parts squared, and the products summed and continuously integrated.

*U. S. No. 2,907,560.* C. K. Stedman. Iss. 10/6/59. App. 1/24/58. Assign. Statham Instruments, Inc.

*Transducers.* A seismometer whose suspended mass is immersed in a liquid that is circulated by movement of the mass, the liquid being circulated in a hydraulic bridge having a diaphragm-type flow detector.

*U. S. No. 2,907,621.* J. D. Eisler and C. F. Hadley. Iss. 10/6/59. App. 12/16/55. Assign. Pan American Petroleum Corp.

*Multiple Trace Recorder.* A seismograph recorder using electrosensitive paper that is drawn under a disk carrying a number of stylii and rotating on an axis parallel to the direction of motion of the paper, the seismic signals being applied to the stylii through a multiplexing system that is electronically triggered by photoelectric relays actuated by a synchronously rotating disk.

*U. S. No. 2,908,342.* O. A. Itria. Iss. 10/13/59. App. 4/19/54. Assign. Texaco Inc.

*Method of Geophysical Exploration.* A method of reducing the source of ghost reflections in seismic prospecting by using an array of vertically spaced shots fired with delay times such that the upward traveling waves from the separate shots will reach the earth's surface in opposite phase so as to cancel each other.

*U. S. No. 2,908,866.* C. A. Heiland and R. F. McCammon. Iss. 10/13/59. App. 4/29/55. Assign. Minneapolis-Honeywell Regulator Co.

*Measuring Apparatus.* A multichannel oscillograph having penciliform galvanometer elements with slip rings that contact brushes on a common connector block that also carries damping resistors.

*U. S. No. 2,908,889.* R. G. Piety. Iss. 10/13/59. App. 12/16/55. Assign. Phillips Petroleum Co.

*Computer.* A cross-correlation computer in which a seismic trace or well log is recorded on an endless magnetic medium and picked up by a number of reproducers equally spaced along the medium over a range commensurate with the wave to be detected, the outputs of the successive reproducers being amplified in proportion to the wave shape to be detected and connected to a circuit for summing the resulting signals from the reproducers.

*U. S. No. 2,908,890.* H. O. Campbell and A. P. Lipski. Iss. 10/13/59. App. 6/27/55. Assign. Continental Oil Co.

*Seisphone and Cable Assembly.* A suspended coil electromagnetic seismometer having an annual outer magnet that is magnetized axially at its midsection and radially at its ends, the entire seismometer being encased in a rubber sheath with arms enclosing the cable leads.

*U. S. No. 2,909,121.* W. B. Gernert, E. H. Phillippe III, and P. A. Ramsdell. Iss. 10/20/59. App. 1/3/56. Assign. E. I. duPont de Nemours and Co.

*Blasting Assembly.* A water resistant explosive assembly in a container having at its upper end a funnel-shaped well with a rubber washer through which the initiator is inserted.

*U. S. No. 2,909,744.* M. DiGiovanni. Iss. 10/20/59. App. 10/22/56. Assign. Statham Instruments, Inc.

*Electrical Accelerometer.* A miniature seismometer whose mass, suspension, and base are made of a single piece of metal and flexure of the suspension is detected by an unbonded resistance wire strain gauge.

*U. S. No. 2,909,759.* G. W. Cook. Iss. 10/20/59. App. 6/15/53.

*Sensitive Vertical Displacement Seismometer.* An earthquake seismometer having a horizontal arm supported by bowed cantilever springs and having coarse control by means of an electromagnet and fine control by means of an electrostatic force system controlled through amplifiers whose input is obtained from a capacitative pick-up.

*U. S. No. 2,910,339.* J. D. Eisler and C. F. Hadley. Iss. 10/27/59. App. 6/19/57. Assign. Pan American Petroleum Corp.

*Electrographic Recording Apparatus.* A seismograph recorder using electrosensitive paper that is drawn under a disk carrying a number of stylii and rotating on an axis parallel to the direction of motion of the paper with signals successively applied to the stylii, the system having interlocks so that the paper does not contact the stylii unless the paper is in motion, and also having glow tubes on the disk in series with the stylii so that operation may be visually observed without recording.

*U. S. No. 2,910,550.* R. O. Soffel. Iss. 10/27/59. App. 4/27/56. Assign. Bell Telephone Laboratories, Inc.

*Wide-Range Automatic Gain Control.* An avc circuit using a push-pull amplifier whose output is rectified, filtered, and applied as a positive bias to both tubes of the same stage of the amplifier.

(See also Patents 2,905,258 and 2,910,133 listed under Well Logging; and Patents 2,906,917 and 2,908,888 listed under Miscellaneous.)

## WELL LOGGING

*U. S. No. 2,901,835.* E. G. Peebles. Iss. 9/1/59. App. 8/1/55.

*Drift Indicator.* A one-shot borehole inclinometer having a pendulum with a pointed stylus at its upper end and a record disk on a piston exposed to drilling fluid so that a record is made by increasing drilling fluid pressure to force the record against the stylus.

*U. S. No. 2,902,603.* M. C. Ferre. Iss. 9/1/59. App. 6/8/53. Assign. Schlumberger Well Surveying Corp.

*Thermally Insulated Scintillation Counter.* A radioactivity logging counter having a double-walled evacuated flask whose inner container has a photomultiplier in its upper end and a scintillation element in a middle compartment and an evacuated compartment at the bottom end.

*U. S. No. 2,902,637.* M. R. J. Wyllie. Iss. 9/1/59. App. 4/29/54. Assign. Gulf Research & Development Co.

*Sampling Drilling Fluid.* A device for obtaining a sample of drilling fluid filtrate and filter cake in a well having a closed container whose cylindrical wall is made of permeable material so that as it is lowered into the well the filtrate will enter the container and also form filter cake on its outer surface.

*U. S. No. 2,902,640.* J. E. Foster. Iss. 9/1/59. App. 12/15/54.

*Detection of Stuck Point in Wells.* A device for locating pipe joints and detecting slight movement of the joint when torque is applied, the device having a permanent axial bar magnet with a soft iron axial extension on one end that is wound with a coil and having disk-shaped pole pieces at the ends of the magnet and end of the coil.

*U. S. No. 2,903,594.* R. E. Fearon and J. M. Thayer. Iss. 9/8/59. App. 7/30/49 and 4/19/54. Assign. Well Surveys, Inc.

*Method and Apparatus for Measuring the Direction Sense of Direction and Energy of Ionizing Processes.* A neutron logging method in which the formations are exposed to fast neutrons and the diffused neutrons returning to the well are detected by electrons generated in the detector, the detector having a collecting electrode and a series of ring electrodes to set up a uniform field between them.

*U. S. No. 2,904,112.* B. F. Wiley. Iss. 9/15/59. App. 1/14/55. Assign. Phillips Petroleum Co.

*Apparatus for Detecting Leaks from Well Bores.* A device for releasing radioactive tracer into well fluid by pressure fracturing of a container and having a radioactivity detector for following the course of the tracer behind the well casing.

*U. S. No. 2,905,258.* R. A. Broding. Iss. 9/22/59. App. 11/26/52. Assign. Socony Mobil Oil Co., Inc.

*Measurement of Seismic Travel Time.* An acoustic logging apparatus in which the travel time of a pulse is measured over a constant interval and converted by a scaling factor and function generator into an integrated velocity-depth curve.

*U. S. No. 2,905,826.* T. W. Bonner and R. L. Caldwell. Iss. 9/22/59. App. 9/30/53. Assign. Socony Mobil Oil Co., Inc.

*Measurement of Gamma Ray Energy Due to Inelastic Neutron Scattering.* A radioactivity method of logging for oxygen, carbon, and sulphur, by irradiating the formations with neutrons of energy sufficient to excite characteristic radiation of the elements and detecting prompt gamma radiation of the characteristic energy.

*U. S. No. 2,906,120.* H. M. Buck. Iss. 9/29/59. App. 4/18/57. Assign. Jersey Production Research Co.

*Pressure Measuring Device.* A pressure logging device in which the well pressure is balanced against the force of a rotating flyball assembly by means of a piston whose deflection interrupts the current through the flyball driving motor whose current is measured.

*U. S. No. 2,906,944.* M. P. Lebourg. Iss. 9/29/59. App. 5/16/55. Assign. Schlumberger Well Surveying Corp.

*Methods for Investigating Wells.* A method of determining the position of a gas-lift valve by attaching a permanent magnet to the movable part of the valve and checking its location with a magnetically responsive casing-collar locator.

*U. S. No. 2,907,111.* J. C. Calkins. Iss. 10/6/59. App. 4/11/58. Assign. Tuboscope Co.

*Tubing Caliper.* A calipering device having a number of pivoted feeler arms the inner end of which controls an erasing magnet traversed by a magnetic record on which a constant signal was previously recorded so that the degree of erasure indicates the position of the feeler.

*U. S. No. 2,907,884.* A. J. Gale. Iss. 10/6/59. App. 6/14/55. Assign. High Voltage Engineering Corp.

*Compact Neutron Source.* A borehole neutron source having an ion accelerator powered by a motor-driven belt-type electrostatic generator.

*U. S. No. 2,908,085.* B. G. Price, F. M. Wood, and J. H. Unger. Iss. 10/13/59. App. 11/15/57. Assign. Tuboscope Co.

*Measuring Instruments.* A self-contained wire-line operated calipering tool having an a-c source connected to a number of differential transformers whose cores are moved by the caliper arms and whose secondary voltages are rectified and recorded.

*U. S. No. 2,908,817.* A. S. McKay. Iss. 10/13/59. App. 6/24/54. Assign. Texaco Inc.

*Measurement of Viscosity.* A device for measuring the viscosity of fluid in a borehole by means of a radioactivity detector centered in the borehole and having on its outer surface flexible spring arms carrying radioactive material so that the deflection of the springs can be measured when the device is pulled upward at a predetermined rate.

*U. S. No. 2,908,823.* J. O. Ely. Iss. 10/13/59. App. 2/18/54. Assign. Socony Mobil Oil Co., Inc.

*Production of Monoenergetic Neutrons.* A radioactivity logging apparatus in which monoenergetic neutrons are generated by bombarding tritium with deuterons and using in the tube two chambers each of which contains a metal that forms a stable hydride with hydrogen and which can be decomposed by heating so that the concentration of ions can be controlled.

*U. S. No. 2,909,661.* F. C. Armistead. Iss. 10/20/59. App. 9/2/54. Assign. Texaco Development Corp.

*Radioactivity Borehole Logging.* A neutron-gamma logging system using a neutron source and detecting gamma radiation returning to the borehole at angles of 30° and at 70° with respect to the borehole axis and comparing their intensities.

*U. S. No. 2,909,923.* K. H. Miller. Iss. 10/27/59. App. 8/26/57.

*Method of Identifying Fluids and Their Points of Influx in a Well.* A method of identifying the location and nature of fluids entering a freshly drilled well by packing the well with granular material of various sized particles so that the fluid flow will cause size segregation, and subsequently coring the material to observe its stratification and fluid saturation.

*U. S. No. 2,910,133.* R. B. Hudson and R. N. Beck. Iss. 10/27/59. App. 12/11/52.

*Method of Continuous Well Logging During Drilling.* A method of logging while drilling by imparting a sonic pulse to the drill stem at the surface by means of an electromechanical transducer, picking up the sonic pulse after reflection from the bottom of the drill string, and observing variation in the amplitude of the reflection as drilling progresses.

*U. S. No. 2,910,587.* A. T. Sayre, Jr. Iss. 10/27/59. App. 12/27/56. Assign. The Pure Oil Co.

*Well Logging Process.* A method of determining the extent of mud filtrate invasion into cores by taking the core with a soluble radioactive tracer in the mud and subsequently cutting the core transverse to its axis and scanning the fresh core surface along various radii with a radioactivity detector.

*U. S. No. 2,910,591.* P. E. Baker. Iss. 10/27/59. App. 9/24/56. Assign. California Research Corp.

*Carbon Logging Through Casing.* A fast neutron-gamma ray logging system in which the disturbing effect of thermal neutron capture rays from iron are eliminated by employing a drilling fluid containing borax or by coating the sonde with a layer of plastic that contains boron.

(See also Patents 2,908,839 and 2,910,592 listed under Radioactivity Prospecting.)

MISCELLANEOUS

*U. S. No. 2,904,406.* P. J. Moore. Iss. 9/15/59. App. 5/4/56. Assign. National Lead Co.

*Hydrocarbon Detection.* A hydrocarbon gas detector of the catalytic filament type in which the filament is flashed to about 700°C. prior to measurement operation at about 300°C.

*U. S. No. 2,905,825.* J. F. Black and E. O. Forster. Iss. 9/22/59. App. 12/7/55. Assign. Esso Research and Engineering Co.

*Method and Apparatus for Measuring Specific Activity of Radioactive Materials in Small Quantities.* A system for measuring concentration of radioactive tracer in a material by placing a small quantity of the material over a calibrated opening in a radioactivity detector.

*U. S. No. 2,906,917.* C. Simpson. Iss. 9/29/59. App. 6/11/57. Assign. U.S.A.

*Trace Identifier for Oscilloscopes.* A system for identifying the traces of a multibeam cathode-ray oscilloscope by intensity modulating the beams in different patterns.

*U. S. No. 2,908,241.* E. T. Todd. Iss. 10/13/59. App. 1/3/55. Assign. General Motors Corp.

*Amphibious Vehicle.* An amphibious vehicle whose wheels are mounted on pneumatic suspensions supplied by a gas source which can also actuate a pneumatic motor to retract the wheels.

*U. S. No. 2,908,888.* R. E. Kirkland. Iss. 10/13/59. App. 3/16/56. Assign. Raytheon Co.

*Acoustic Logs.* A Doppler system for measuring the speed of a ship by transmitting a c-w acoustic signal and observing the frequency difference between the transmitted wave and the received reflected wave.

*U. S. No. 2,908,902.* J. W. Gray, E. B. Hales, and I. A. Greenwood, Jr. Iss. 10/13/59. App. 2/17/54. Assign. General Precision Laboratory Inc.

*World-Wide Navigational System.* A dead reckoning type of navigation system in which the indi-

cations of a radio-echo speed and direction measuring unit are combined with those of a flux-gate compass and free gyro by a computer so as to give instantaneous position data.

*U. S. No. 2,908,903.* F. B. Berger, W. J. Tull, and J. W. Gray. Iss. 10/13/59. App. 10/3/51. Assign. General Precision Laboratory Inc.

*Course and Speed Indicating System.* A Doppler-type airplane course and speed indicator in which the frequencies of energy reflected from areas spaced transversely of the airplane are compared with each other to determine drift, and the frequencies of energy reflected from areas spaced longitudinally of the airplane are compared to determine ground speed, the antenna system being arranged to transmit conical patterns that provide maximum reflected energy concentrated in a frequency spectrum of minimum width.

*U. S. No. 2,910,665.* J. E. Hawkins. Iss. 10/27/59. App. 4/2/56. Assign. Seismograph Service Corp.

*Radio Acoustic Ranging System.* A radio acoustic ranging system in which the mobile station transmits both a radio and an acoustic signal and the radio signal initiates operation of a c-w radio transmitter at the transponder, the transponder radio being modulated by the received acoustic signal.

SELECTED LIST OF U. S. PATENTS ISSUED DURING SEPTEMBER AND OCTOBER OF 1959

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* A key to the subject classification system will be found in GEOPHYSICS, v. 12, pp. 256–264 (April, 1947).

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# REVIEWS

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*Researches in Geochemistry*, edited by Philip Hauge Abelson, John Wiley and Sons, Inc., New York, 1959, 511 pp., $11.00.

Research in geochemistry has advanced so rapidly the past few years that it has been difficult for most investigators to keep abreast of the various facets of this expanding science. In 1957 the Geophysical Laboratory at Johns Hopkins University initiated a seminar series in geochemistry in which outstanding scientists were invited to participate. This book represents a compilation of the lectures presented at this seminar.

The list of contributors reads like a "Who's Who" of geochemistry. Libby discusses hydrolgoy studies based on the use of tritium from thermonuclear weapons, and practical applications of tritiated water in determining local flow patterns, run-off and re-evaporation rates. DeVries reviews applications of carbon-14 dating to Pleistocene chronology, and the variation in carbon-14 concentrations with time and geographic location. The current status of isotopic methods of age determination (uranium-lead, potassium-argon, and rubidium-strontium) are discussed by Tilton and Davis. Epstein reports on the measurement and value of $O^{18}/O^{16}$ ratios and Ault on $S^{32}/S^{34}$ ratios in studying natural processes.

An interesting chapter on geochemical methods for differentiating rocks of marine origin from those of fresh-water origin is by Keith and Degens. Trace elements such as boron, lithium, sulfur, and fluorine appear to be promising criteria for differentiation. Recent work on the equilibrium relations of carbonate mineral systems is reviewed by Goldsmith. An excellent chapter on the origin and relationships of mineral assemblages of the Green River formation in Wyoming, Colorado, and Utah is presented by Milton and Eugster.

Arrhenius discusses rates and conditions of sedimentation on the ocean floor, particularly the east equatorial Pacific, and Garrels describes chemical reactions at the temperatures and pressures characteristic of sedimentation. Abelson, who sponsored the seminar and edits the book, contributes a chapter on the organic substances found in sedimentary rocks. This is followed by a discussion on the origin of petroleum by Hanson.

The use of geochemical anomalies in prospecting for ore bodies, including case histories, is presented by Hawkes. Other chapters on the geochemistry of ore deposits and solutions are by Krauskopf, Barton, and Kullerud.

Thompson, Boyd, and Eugster discuss metasomatic and metamorphic processes; Chayes describes variations in X-ray diffraction due to subtle mineralogical transitions; and Reed reviews the use of neutron activation in analyzing for trace elements at the parts per million level in meteorites. The two final chapters discuss chemical conditions below the earth's crust, McDonald using the evidence of chondrites to describe the earth's composition and Clark reviewing phase changes and equations of state at the high pressures of the earth's core.

In general, most of the chapters are well written, the technical data are excellent and up to date, and conclusions are well documented. Each chapter contains an extensive bibliography, in one case nearly 60 references.

The book is not intended for the layman. Although the authors generally introduce their subjects in readily understood terminology, the discussions are highly technical and generally in the area of basic research. It will, however, be of great interest to the research geophysicist, geologist, or geochemist who wants to be brought up to date on developments in geochemistry without going through the voluminous number of papers that have been published in recent years.

JOHN M. HUNT
Jersey Production Research Co.
Tulsa, Oklahoma

*Geochemical Methods of Prospecting and Exploration for Petroleum and Natural Gas*, English translation edited by Paul A. Witherspoon and William D. Romey, by A. A. Kartsev, Z. A. Tabasaranskii, M. I. Subbota, and G. A. Mogilevskii, University of California Press, Berkeley and Los Angeles, 1959, 349 pp., $12.50.

This book is a compilation of surface and subsurface methods of geochemical prospecting for petroleum that have been investigated by the Russians over the past 30 years. The methods are based on the determination of gases, bitumens, or other naturally occurring materials that are frequently found associated with petroleum accumulations. The first chapter deals with the composition of petroleum and associated gases and waters. The physical-chemical conditions under which petroleum forms, and the causes for variability in composition are briefly reviewed. This is followed by a short section on the classification of geochemical methods into direct procedures involving the detection of gas or bitumens, and indirect procedures involving the detection of inorganic salts and micro-organisms. Succeeding chapters discuss these techniques in considerable detail, pointing out their advantages and disadvantages.

The book will interest anyone who wants to be brought up-to-date on geochemical methods of petroleum prospecting since the Russians have probably done more of this work than anyone else. However, it is of little practical value to the field man who wants to know if these techniques will help him find oil. There are few examples given of oil being found by these methods, and most of these are in the section on microbiology. Also, several procedures are discussed in detail which the authors admit are of limited value.

As in many Russian books nearly all of the references are to Russian work. Also, many of the illustrations, particularly the maps, do not have enough information on them to interpret the authors' comments properly. The roughness of the translation in spots is probably due to a lack of suitable English words. However, the technical material is good. Most of the experiments are well thought out, and the authors are cautious in drawing conclusions where the data are controversial. For

example, the authors agree with many U. S. investigators that surface methods of prospecting, particularly soil and radioactivity studies, may not be indicative of petroleum, but may be surface expressions of buried structure. Subsurface methods appear to be better indicators of oil.

The book is particularly recommended for research personnel, and it will also interest the operating geologist or geophysicist who wants to know more about geochemical prospecting for petroleum.

JOHN M. HUNT
Jersey Production Research Co.
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Surface Motion from Large Underground Explosions, D. S. Carder and W. K. Cloud, *Journal of Geophysical Research*, Vol. 64, 1959, pp. 1471–1487.

This paper was produced by Federal Government employees as a part of their official duties. It is not copyrighted.

Direct-recording, standard strong-motion seismographs were used to measure the surface disturbances derived from large underground explosions including nuclear detonations.

Because of the large possible ranges in magnitude of the ground motions to be observed, it was necessary to predict the expected ground effects in advance of preparation of the seismic instruments for actual recording purposes. This procedure insured, to some degree, that the seismic recording would contain the desired data in a measurable form. The method of scaled similarity was used on information obtained experimentally from previous smaller blasts to estimate zero-to-peak ground displacements and accelerations for the anticipated ground effects due to larger release of explosive energy. With this preparation, useable seismograms of the Rainier nuclear explosion were obtained with ten Coast and Geodetic strong-motion seismographs.

Line tracings of the certain strong motion seismograms of displacements and accelerations are a very significant portion of the report. Accuracy of the seismogram representation is discussed. Derived accelerations and displacements from the recordings are tabulated and briefly described. Several of the Rainier strong-motion records were analyzed utilizing the electric analog-type response spectrum analyzer system at the California Institute of Technology Earthquake Research Laboratory. Results of the analysis are presented as graphs of relative maximum velocity plotted against undamped natural period. Velocity-spectrum data for earthquakes of known magnitude were compared with those of the underground nuclear explosions. In this manner the relative response of certain theoretical structures to the ground motion caused by the Rainier event were estimated. Assuming similar conditions to those associated with an earthquake, together with allowances for obvious differences, the magnitude of the Rainier disturbance was estimated as approximately 4.0. References to blasts recorded at different places in the world are also mentioned for the purpose of comparison. Empirical formulae for seismic energy at any distance from the origin are given. Computed and actually measured data are compared in a clear graphical manner. Departures between the observations and computations are briefly discussed.

Small space is given to the HARDTRACK II series of shots, however, the point was made that formula developed for Rainier and smaller blasts gave fair accuracy for the larger explosions but with certain listed limitations. A feature of noteworthy importance was observed in reference to ground amplitudes on deep alluvium as compared with amplitudes at approximately the same distance on so-called solid rock. As was predicted, the amplitude on the alluvium was observed to exceed twice the amplitude of hard rock. In all, thirteen figures and seven tables adequately display the results of the study to the reader. A short list of references follows the text of the report.

It is the opinion of the reviewer that the report would have wider reader appeal if a very brief coverage of the fundamentals involved in the study had been included with the descriptive materials. Many readers of the *Journal of Geophysical Research* do not possess the technical background of "seasoned" seismologists. The paper is certainly a valuable contribution to the published data on surface motion of the ground due to large underground blasts and it will serve as an excellent infor-

mation source for experimental workers in this field. The reading of this paper is a must for seismologists contemplating studies of this kind.

JOSHUA L. SOSKE
Stanford University
Stanford, California

Underground Nuclear Detonations, G. W. Johnson, G. H. Higgins and C. E. Violet, *Journal of Geophysical Research*, Vol. 64, 1959, pp. 1457–1470.

The authors of this paper have diligently compiled pertinent data concerning eight underground nuclear explosions at the Atomic Energy Commission Test Site in Nevada. Equivalent energy release, burial depths, effects of blasts, date and time of detonations, elevations and locations of the shots in terms of latitude and longitude are given. These data are an important source of information to those making studies of recordings of the seismic events produced by these detonations.

Another important disclosure of the paper is the experimental demonstration that the radioactivity from nuclear explosions can be effectively contained by proper burial and stemming of the entrances to underground cavities containing the nuclear devices. The findings derived from drilling into the rocks that were melted and disturbed by the blasts are clearly and interestingly described.

An exceptional feature of the article is the presentation of quantitative physical data on the rocks containing the devices and the results of the blasts. Details of local effects are also described and demonstrated by cross-sections and line-sketches depicting post-detonation studies of the larger blasts.

The discussion of earth motion is of particular interest to seismologists. Both acceleration and displacement measurements were made. A maximum displacement of 1 ft and an acceleration of 6 g were measured near surface zero in the case of Rainier, a 1.7 kiloton equivalent of TNT, explosion which was buried to a depth of 790 ft. Seismic waves initiated by the Rainier event were detected up to 1,000 miles in the continental United States and very weak seismic waves were observed at College Station in Fairbanks, Alaska at a distance of 2,200 miles. The Blanca event, a 19.0 kiloton equivalent of TNT buried in bedded tuff to a depth of 835 ft resulted in a measured vertical displacement of approximately 30 in near surface zero. Strong motion instruments were used to study the local seismic effect. Many temporary seismographs were used to observe the seismic events out to distances of 2,400 miles. Seismic observations on the Blanca event were available from regular seismograph stations all over the world. Energies of the seismic waves are correlated with the magnitudes of the yield in kilotons of TNT equivalents of the various explosions.

Arrival times of shock wave were computed and closely correlated with the observations. As the shock wave (Rainier event) propagated outward, it crushed the medium to a radius of 130 ft where the pressure was 1.4 kilobars. The elastic radius was estimated to be 285 ft horizontally and 305 ft vertically.

This article is recommended by the reviewer as a valuable exposition of observation and interpretation without resorting to speculation. It is a contribution to the literature on heavy blasts, and will be found useful to those who are interested in the phenomenology of such high energy events. A list of 21 references is provided at the end of the paper.

JOSHUA L. SOSKE
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Stanford, California

Amplitudes of Seismic Body Waves from Underground Nuclear Explosions, Carl Romney, *Journal of Geophysical Research*, Vol. 64, 1959, pp. 1489–1498.

This paper is a report on seismic observations from approximately 28 seismograph stations distributed, from the site of underground nuclear explosions in Nevada, eastward to a point in the State of Maine, over a distance of 4,000 km. Seismograms of a dozen or more permanent seismograph sta-

tions in United States and Canada were also studied. Numerical data for six explosions are given. The yield range in equivalent kilotons of TNT for these shots is 0.072 to 19.0 kt. Only Rainier, Logan and Blanca produced measurable body waves at distances beyond 300 km.

The more pertinent results described by the paper are, (a) ground amplitude for the smaller shots appear as a linear function of the yield, (b) the linear relationship between amplitude and yield does not hold for large explosions, (c) amplitude of the longitudinal waves referred to as *Pn* waves varied as the inverse cube of the distance between 200 and 1,000 km from the origin, (d) beyond 1,000 km distance from the origin, the amplitude of *Pn* became too small to measure, however, other later *P* waves of a higher apparent surface velocity were observed beyond 1,000 km, and (e) beyond 200 km the amplitude fell off as expected from earthquake studies except for a low-amplitude region between 3,300 and 3,500 km.

The observed apparent shadow zone in *Pn* beyond 1,000 km to approximately 2,000 is weakly correlated with B. Gutenberg's postulation that a shadow-zone is caused by a low-velocity layer within the mantle at a depth of about 100 miles.

It is thought by the reviewer that the study of this shadow-zone, when combined with that of surface waves, may give a strong hint in determining whether or not an earth disturbance is caused by an explosion or a natural earthquake. The postulation is that an underground nuclear detonation may be encircled by a shadow-zone consisting of a circular band of inside diameter about 1,200 miles and outside diameter approximately 2,400 miles.

It is noteworthy that direction of the first motions recorded by the seismographs was not always compressional. For distance less than 700 km the first motions observed were compressional, beyond this distance some clear rarefactional first motions were observed. This problem was not resolved in the report.

Shear waves, arriving with a velocity of 3.5 km/sec, were observed out to distances of 2,000 km. In general, the shear waves were not examined as closely as the faster longitudinal waves.

Long period surface waves were observed at permanent installations of earthquake seismographs. Unexpected Love waves were detected at Berkeley, Palisades and Resolute Bay. The origin of the Love waves is not given in detail though the writer believed that these waves are due to mode conversion near the source by a process not understood at the time of writing.

Magnitudes of the disturbances according to the Richter scale were computed from Wood-Anderson torsion seismograph recordings of the shear-wave amplitudes. These data given in table form are in fair agreement for the various detonation events. The magnitude ranged from 3 to 5 for the four strong underground explosions. A formula is given for computing the earthquake magnitude of the earth disturbances. Because of general interest and its simplicity, the equation for magnitude $M$ (Richter scale) is reproduced,

$$M = 3.65 + \log Y,$$

where the constant, 3.65 is an average value for 5 of the larger shots and $Y$ is the yield in kilotons of TNT equivalent.

Six line figures and four tables are used to exhibit data. A list of sixteen references is given at the end of the article.

The reviewer compliments the writer for this well-prepared paper and illustrations. Reading of this report is recommended for those interested in studying observable seismic effects derived from underground explosions. It is a good contribution to the literature and observed data on the subject.

Joshua L. Soske
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Stanford, California

Role Played by the Charge Depth on the Amplitude of Seismic Waves Generated by an Underwater Explosion (in French), L. Grinda, *Bollettino Di Geofisica Teorica ed Applicata*, Vol. 1, 1959, pp. 161–174.

The author had the opportunity of observing the seismic waves, detected by a vertical short pe-

riod Grenet seismograph located in Monaco, resulting from numerous underwater explosions occurring in known conditions. The ranges extended from 5.5 to 91 miles, the depths from 22 to 469 ft, and the charge sizes from 320 to 2,208 pounds. He found that the amplitudes increase with depth up to a maximum occurring at an optimum depth. The periods correspond to the pseudo-period of pulsation of the gas bubble produced by the charge and decrease with an increase in depth of the charge. The relief of the ocean bottom plays an important role on the type and character of the propagated waves. In an attempt to interpret the results, the author describes the succession of events occurring during an underwater explosion. A shock wave is created when the detonation wave reaches the surface of the charge. In this shock wave, the pressure pulse has a steep leading edge followed by an exponential decay. At a distance of about 15 times the charge radius, the velocity of propagation of this pressure pulse reduces to that of an acoustic wave. The pulsation of the gas bubble produced by the explosion generates secondary pressure pulses whose amplitude maxima decrease rapidly from one to the next. These pulses are very different from the shock pulse. They present no steep leading edge, the maximum pressure is only 10 to 20 per cent of that of the shock, and the trailing edge lasts much longer so that the pulse has a much larger time constant. The pressure impulsion, defined as the time integral of the pressure pulse, is generally larger in the first secondary pulse than in the shock pulse. After a rapid description of the surface phenomena resulting from the explosion, the author gives his interpretation of the experimental observations. A substantial portion of the energy released by the explosion passes into mass movement of the water which acquires kinetic energy. This kinetic energy is then redistributed among the secondary pressure waves. The gas bubble behaves as a regulator of this energy distribution. The shock wave delivers to the ground seismic energy of large amplitude and very high frequency which is rapidly attenuated, while the secondary pressure waves deliver low-frequency energy which may propagate much farther. These conclusions are supported by the following three constatations:

1. The period of the detected waves corresponds to the pseudo-period of oscillation of the gas bubble.
2. The detected amplitudes increase rapidly with depth of the charge which would not be the case for the shock waves.
3. The characteristics of the waves detected are more logically explained as resulting from the impulsion contained in the secondary pressure waves than from that contained in the shock wave.

From a practical standpoint, this means that the travel time must be referred to the time of occurrence of the first secondary pressure wave rather than that of the explosion.

Geophysicists experienced in marine work are well aware of the presence of these secondary waves, but it seems that most of their efforts have been directed to prevent their occurrence as exemplified by the following literature references and patents. This article may suggest a somewhat different approach.

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U. S. Patent No. 2,877,859. W. C. Knudsen—Offshore Seismic Prospecting.

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Acoustic Velocity in Porous Media, James E. Berry, *Journal of Petroleum Technology*, Vol. 11, 1959, pp. 262–270.

This paper is a very adequate attempt to gather data on the velocity-porosity relationship and to combine these data with some original work done in the Socony Mobil Oil Company laboratory.

Mr. Berry compares the relationship between porosity and a linear-time plot vs. a porosity and linear-velocity plot with the conclusion that the linear time appears to be better because it more closely describes porosity in dirty sands—there being essentially no difference between the two types of plots in clean sands.

A normalizing technique is presented to correct for the effect of depth on the porosity-velocity relationship. A graph is shown for the correction of consolidated and unconsolidated porous media based on pressure difference with depth. This technique appears to be as good as the $C\Delta_t$ method of correction in current use, as presented by Tixier & Alger, S.P.E., 1958.

A study of thin sections of sediments that appear megascopically identical indicates the compaction factor of granular sediments is related to the orientation of the sand grains, i.e., those granular sediments which have the grain faces in contact are consolidated, those sediments having the same overburden pressure but the sand grains having more point contacts appear on the velocity log to be unconsolidated.

Velocity of porous media is affected by cementation, especially in the case of the point-contact granular sediments (unconsolidated sands), for the obvious reason that the presence or absence of cementing material in the interstices of the grains profoundly increases the ability of sound to travel directly through the rock rather than take the tortuous path dictated by an uncemented sand, assuming that the cementing material conducts sound as well as the sand grains themselves. The effect of cementation on the acoustic velocity is not necessarily dependent on overburden pressure.

Mr. Berry does not agree with Wyllie et al. (1958) that the apparent decrease in velocity opposite oil sands is due to attenuation when one considers that the borehole fluid, mud cake and invaded zone must be taken into account. Mr. Berry does concede that in high porosity oil or gas sands, the porosities indicated will be higher than actual.

Mr. Berry shows that all the factors that plague the log interpreter such as cementation factor, saturation exponent, and clay content have not been solved but have been avoided by agreeing with previous authors that a qualitative interpretation can be made in dirty sands and a semiqualitative interpretation can be made in clean sands.

K. F. KENNEDY
Gulf Oil Corporation
Los Angeles, California

# PUBLICATIONS RECEIVED

## BOOKS

Modern Electronic Components, G. W. A. Dummer, Philosophical Library, $15.00.
Glossary of Meteorology, edited by Ralph E. Huschke, American Meteorological Society, Boston.
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Zeitschrift für Geophysik, v. 25, n. 2 (1959)

# MEMORIALS

JAMES ANDREW BROOKS, JR.

The many friends of JAMES ANDREW BROOKS, JR. were shocked and saddened to learn of his untimely death on Sunday, July 19, 1959. He suffered what was at first thought to be a mild cerebral hemorrhage on Saturday. His condition grew worse and the end came unexpectedly the next afternoon. Jimmie was born in Houston June 9, 1904. He attended grammar school and high school in Houston and went one year to The Rice Institute. When his family moved to New York, he enrolled at Colgate University where he received a B.S. degree in Geology. His first work in geophysics was for Gulf Production Company (now Gulf Oil Corp.) in 1928. He worked with one of the German Seismos crews engaged in refraction shooting in the Gulf Coast area. He was employed by Humble Oil & Refining Company March 22, 1930 as a computer on a refraction seismograph crew. Shortly afterward he went to the Netherlands East Indies where he did refraction seismic work for two years, serving under W. R. Feather as Party Chief and E. S. Sherar as Supervisor. On his return to the United States he again joined Humble and for several years he was party chief of a seismic crew. In March 1942 he was brought into the Houston office as a Staff

Geophysicist. In November 1942 he entered the United States Navy. During World War II Jimmie served with the rank of Lieutenant in the Bureau of Ships in Washington, D. C. for a short time before being assigned to a Naval Mine Warfare group where he spent the remainder of his Naval service.

Jimmie Brooks ranked high in his profession. He was well known as a thorough and a competent geophysicist. He was among the first to recognize the need for detailed subsurface velocity information. From the early days of reflection seismograph work he strongly advocated more velocity determinations in drilled wells. For a number of years he served as Humble's representative with the Southern Seismic Well Shooting Association. He was co-author of a paper, "A Note on Well Shooting Data and Linear Increase of Velocity."

It can be said of Jimmie that he led a full life. He was an active worker in his church, Christ Church Cathedral of Houston. He not only got pleasure from his chosen profession but he also had many and varied other interests. He was an ardent hunter and an expert amateur photographer. He had been a licensed airplane pilot for a number of years, and was owner of his own plane. Brooks was a member of the Society of Exploration Geophysicists for twenty-four years. In addition he held membership in the American Association of Petroleum Geologists, the Geophysical Society of Houston, the Houston Geological Society, the Houston Photographers Society, the Airplane Owners and Pilots Association and he was president of the Southwest Bowling Corporation. He was among the organizers and first members of the Houston Geophysical Club and served on its original board of directors.

Brooks is survived by his wife, Vera Hamilton Brooks, a son, James A. Brooks III, a daughter, Mrs. Virginia Kidd, his mother, Mrs. J. A. Brooks and two grandchildren. Jimmie's graciousness, sincerity and devotion to duty will remain as an example to his many friends and associates. He will be missed by all of them.

HOMER G. PATRICK

## ROSWELL STEWART EPPERSON

ROSWELL STEWART EPPERSON died of a heart attack in San Angelo, Texas, on August 13, 1958, after a prolonged illness.

"Epp," as he will be remembered by his many friends, was born in Cameron, Texas, on February 6, 1904. After graduating from Cameron High School, he attended Texas A&M College and the University of Texas Medical School as a pre-med student.

Early in the history of geophysics, Epp chose this field as his career, starting to work for the Gulf Oil Corporation in 1925 as an engineer on a refraction seismograph crew. He joined Humble Oil & Refining Company on June 1, 1926 to work on a seismograph crew in Louisiana and the Texas Gulf Coastal area.

ROSWELL STEWART EPPERSON

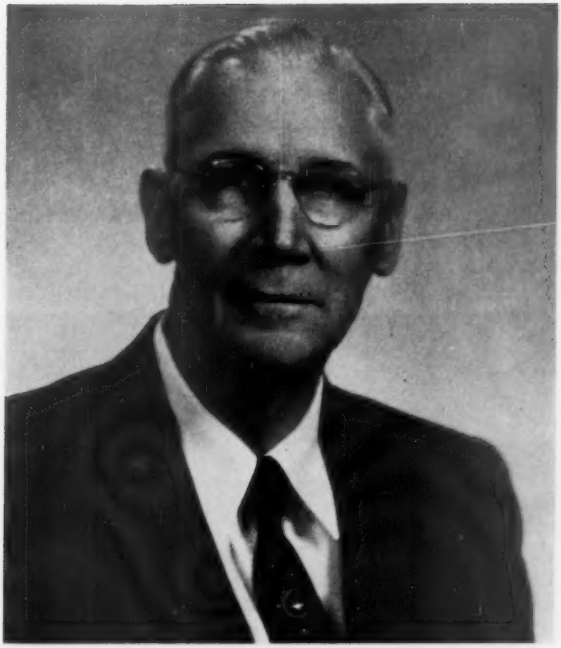
While stationed in Wharton, Texas, he met Miss Sibyl Neff and on June 16, 1928, they were married. His wife and a son, Stewart, survive him.

In 1928 Epperson went to Venezuela where he worked for nine months as a shooter and operator on a seismograph crew. Following his return to the United States on August 15, 1929, he worked on Humble geophysical crews in Louisiana, Texas and New Mexico. His work eventually took him to West Texas where he was made Party Chief. West Texas was much to his liking. In this vast territory, full of activity, where there was always a new challenge, he had his greatest satisfactions from his life's work.

Epp's keen interest in people made him many friends among farmers, ranchers and oil men throughout his lifetime. Strong devotion to his family, faithfulness to his Company, love for his work and loyalty to and pride in the men working with him were the dominating factors in his life.

His many friends and fellow workers will long remember Epp for his integrity and philosophy of life.

H. L. VOELKER



WILLIAM SCHRIEVER

WILLIAM SCHRIEVER was unable to attend the meeting of the Society of Exploration Geophysicists at which the society conferred honorary membership upon him. He died on November 20th, 1958, at the age of 64 after a protracted illness, being survived by his wife, a son and a daughter. The Sooner state was the locale for his life's work and he was a "Sooner" in the field of American exploration geophysics. He was preparing students for entry into this field of professional activity when this was being done at few, if any, other educational institutions. Through his teaching activities the University of Oklahoma has contributed a substantial segment to the membership of SEG and many of his students have become prominent in geophysical exploration. For about thirty years Doctor Schriever was recognized as the top educator in the field of geophysics in the state of Oklahoma.

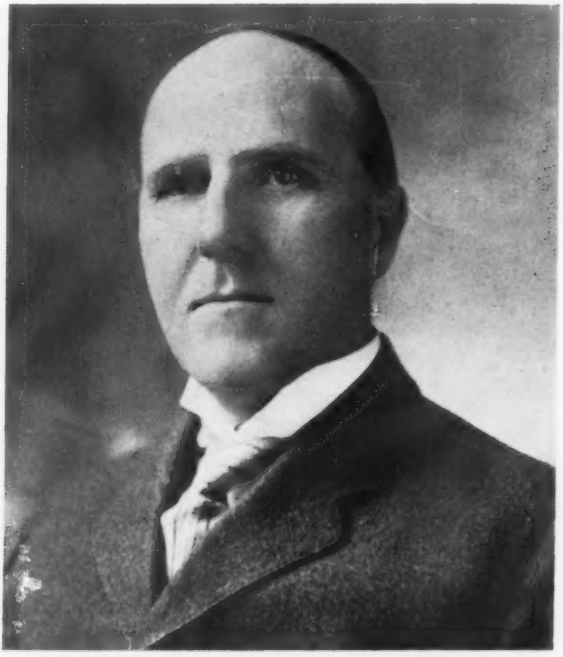
Like most of his contemporaries in the earliest years of geophysical exploration in America, Doctor Schriever was trained as a physicist. He was awarded his Ph.D. degree in physics at the University of Iowa in 1921. His subsequent professional life was spent entirely at the University of Oklahoma.

As a part of his activities in education Doctor Schriever himself and together

with his students engaged in a substantial program of research, a great deal of which dealt with the physical properties of earth materials and techniques for measuring them. His last paper was published in GEOPHYSICS only one month before he died.

The success and loyalty of the students he has taught are often the greatest rewards a teacher can enjoy. In these respects Doctor Schriever was exceptionally well rewarded. In him, his students, the society and the profession have lost an active force in the development of their potential, a source of inspiration and a friend.

E. A. ECKHARDT



CHARLES EDWIN VAN ORSTRAND

CHARLES EDWIN VAN ORSTRAND died in Pekin, Illinois on July 23, 1959. His health had been failing for several years. About nine years ago blindness overtook him. He had been bedfast for five and one-half months prior to his passing. He had been retired from the U. S. Geological Survey since 1940.

C. E. Van Orstrand was born February 8, 1870 near Pekin, Illinois. His father was Charles Gregory Van Orstrand; his mother the former Mary Margaret Van Deusen. He never married and has no close survivors. He attended the

University of Illinois, obtaining a B.S. degree in Civil Engineering in 1896, and a B.S. degree in Mathematics and Astronomy in 1897. He attended the University of Michigan obtaining a M.S. degree in 1898.

Mr. Van Orstrand entered the Government service as a computer in the U. S. Naval Observatory "Nautical Almanac Office." He was promoted to an assistant in 1899. He came to the U. S. Geological Survey as an Assistant Physical Geologist in 1901 under the supervision of the late George F. Becker, who shaped his career in geophysics. Advancement to Associate Physical Geologist came in 1913, to Physical Geologist in 1915, and to Geophysicist in 1924; all positions being in Washington, D. C. He was lecturer in the Post Graduate School of George Washington University on Mechanics from 1910 to 1917, and on Mathematical Physics from 1917 to 1931.

Mr. Van Orstrand had wide interests, as indicated by his former membership in scientific societies: A.A.A.S.; Physical Soc.; Amer. Inst. Min. Met. Engrs.; Mathematical Soc.; Mathematics Ass'n.; Astronomical Soc.; Meteorological Soc.; Seismological Soc.; Amer. Geographical Soc.; Amer. Ass'n Petroleum Geologists; Genetics Ass'n.; Forestry Ass'n.; Amer. Geophysical Union; Geol. Soc. Wash.; Philos. Soc. Wash.; Wash. Acad. Sci.; Physical Soc., London.

His list of publications is extensive and varied, including the subjects; mathematical physics, heat conduction, mathematics, temperatures in flowing wells and springs, deep earth temperatures, and mathematical tables. He was the author with George F. Becker, of the Smithsonian Mathematical Tables and Hyperbolic Functions, 1909. Since retirement, he had worked on another book of mathematical tables that was to contain 8-place functions, but it is believed that manuscript was not finished for publication. The writer, under his able guidance, computed extensive 25-place tables of the exponential functions.

Mr. "Van," as his associates remember him, was a devoted individual to science, to his church, he was a Methodist, and to his mother. He was always willing to give his capable help to anyone requesting it. His work, particularly in earth temperatures, will be often referred to in geophysical literature.

H. CECIL SPICER

## ROBERT LEE MITCHELL

ROBERT LEE MITCHELL died on the morning of November 8, 1959 in Houston, Texas. His untimely death from cancer at the age of 38 cut short the career of an outstanding exploration geophysicist.

"Mitch," as he was known to his many friends, was born in Healdton, Oklahoma on December 5, 1920. He spent all of his boyhood in Seminole, Oklahoma where he obtained his primary education. He moved to San Antonio, Texas in his early youth and graduated from Brackenridge High School in 1939. Mitch attended Southwestern State Teacher's College in San Marcos, Texas and St. Mary's University in San Antonio until late in 1942. He enlisted in the Signal

ROBERT LEE MITCHELL

Corps in January, 1943 and attended Oregon State College for 12 months under the A.S.T.P. and served with distinction as a Staff Sergeant in the Asiatic Pacific theatre until his discharge in 1946. After the war, Mr. Mitchell continued his education for another year at the Texas College of Arts and Industries in Kingsville, Texas.

Mitch joined Seismic Explorations, Inc. of Houston, Texas as a Junior Observer on June 6, 1947. His promotion to Observer was rapid and during the next six years he worked on seismic field parties as Observer and subsequently as Computer in Arkansas, East Texas, Louisiana, and North Dakota. Mr. Mitchell was promoted to Seismic Party Chief in July, 1953 and served in that capacity in Louisiana, East Texas, Central Texas and the Gulf Coast. In 1958 he was transferred to the SEI Houston District Office as a geophysicist. This gave him an opportunity to complete his college education at the University of Houston where he received a B.S. degree in Electrical Engineering with a minor in Mathematics in 1958.

Robert Lee Mitchell was a man of many and varied interests. His main hobbies were hunting and fishing and he was a voluminous reader of a wide range of

technical literature. He wrote several short stories based on Texas and southern history which he someday hoped to publish. These interests were supplemented by that of a new home which was a great source of enjoyment for Mitch and his family in the closing years of his life.

Mitch's friends and associates respected him for his determination, honesty and sincerity. It was characteristic of him that his natural optimism and cheerful attitude were never dulled in his courageous fight against the disease that eventually claimed him.

He was a member of the Society of Exploration Geophysicists, the Geophysical Society of Houston, and the First Baptist Church of Spring Branch.

Mitch is survived by his wife, Thelma, two daughters, two grandsons, his mother and his sister. All of his many friends deeply regret his passing.

E. F. ZAGST

## SLOTNICK MEMORIAL PRESENTATION

Following is the text of an address given by Cecil H. Green, Honorary Member, at a meeting of the Geophysical Society of Houston, held November 23, 1959, in honor of the late MORRIS MILLER SLOTNICK, on which occasion Mrs. Slotnick was presented an inscribed copy of the Memorial Volume, *Lessons in Seismic Computing*.

This gathering comprises a most important event for all of us in the Petroleum Exploration Industry.

I feel that its purpose is threefold—first, to honor Dr. Morris Miller Slotnick, who continues to live in our hearts and memories; second, to honor and to express appreciation to a gracious lady, his wife; and finally, to congratulate ourselves for the good fortune of having acquired a valuable addition to our technical geophysical literature.

Our threefold purpose is represented by a very fine geophysical reference volume, fresh from the printing presses of the George Banta Company, Inc. of Menasha, Wisconsin, of which a special copy will be given this evening to Mrs. Esther Slotnick.

It is important for all of you to know that this memorial volume under the title *Lessons in Seismic Computing*, comprises a compilation of a series of lessons prepared by Dr. Slotnick over a period of several years, starting in 1949, for the benefit of the Humble Geophysics Department.

The Humble Oil & Refining Company is due commendation for its generous, and may I say broad-minded, decision to make the Slotnick notes available outside of the company, that is, for the benefit of the entire exploration industry, by turning all rights of ownership of the notes over to Mrs. Slotnick.

Thereupon, Mrs. Slotnick had the choice of converting the manuscript into

a strictly commercial textbook, or of making it available to the Society of Exploration Geophysicists. I happen to know that the publishing firm of John Wiley and Company made a real offer to Mrs. Slotnick along with the opportunity for royalty income, and yet she chose to give the manuscript with all publication rights to the SEG.

So, we as members of the SEG can and should feel downright humble when we say "Thanks" to Mrs. Slotnick for this valuable gift, which not only adds to the general knowledge, but in turn tends to increase the relative stature and importance of our Society in the wide field of Earth Sciences. In short, Mrs. Slotnick actually honors the Society greatly with her kind and unselfish gesture!

In continuing to speak for the Society (and I thank both Dave Carlton and President Tom Hall for this great privilege) I would take the liberty of speaking also for Mrs. Slotnick. Thus, I know she would like for me to express her appreciation to Dave Carlton for an appropriate preface which he contributed to the volume. Then, I know she would join with all of us in expressing "Thanks" to Dick Geyer, the special editor for the volume. The least I can say is that Dick Geyer did a masterful job of checking and proofreading, so that the text and illustrations are in exact accord with the manuscript, all composed into a volume of first-class appearance.

As a positive indication of the volume's immediate fine reception, I am sure Mrs. Slotnick, and all of you, will be glad to know that even at this early date, its sales have matched the over-all Banta Company printing costs.

Speaking for all of you gathered here this evening, I would like to assert to Mrs. Slotnick that we view this new volume not only as a distinct contribution to our scientific literature, but more importantly as a symbol of a great and wonderful human being.

I say this because "Moe" Slotnick was an outstanding teacher, not only because of his brilliant mathematical prowess and natural ability to project information to others, but because of his great liking for, and kindly understanding of, human nature. He liked people to the point of rendering help to others where even abundant patience would be required. Like the true teacher, he took special delight and satisfaction in seeing his one-time "pupils" get ahead. I am sure that many of us have heard him refer with no uncertain pride to some successful executive as "one of my boys, you know."

Moe had a true sense of human values in that he had just naturally discovered that the real thrill in life comes from giving and doing for others—that friends, rather than material things, comprise our greatest possessions and assets. He knew also that we thrive and get ahead in this world with the help of our fellow men, and not in spite of them. He seemed also conscious of the fact that what really counts is not so much what we think of ourselves as just how others appraise us.

As an exponent of mathematics, which is truly an exact and unequivocal science, it would have been easy for Moe to have lacked tolerance of under-

standing. Yet, in his writings he made a special point of warning that in applied geophysics, wherein we combine art with science, a mathematical approach may provide the necessary framework, but its effect must of necessity be tempered with judicious amounts of experimentation and practical experience in working towards a best solution for a situation.

Thus, Moe was a most worthwhile type of scientist, for while his head could in the clouds of theoretical knowledge, still his feet were planted firmly on the ground. It was natural for him to be a proponent of the importance of collaboration, where more was to be obtained from effective teamwork of geologist and geophysicist rather than from either one trying to go it alone, or where the researcher and the operating man have a mutual high regard for the other's importance to the total effort.

For those of you who haven't read Dave Carlton's preface in our memorial volume, I wish to state that Dr. Slotnick contributed much to the SEG through his numerous papers dealing with the interpretation of geophysical data. Also, he served the Society well as its editor during the period 1937 and 1938.

He was born in Russia in 1901 and, like many of us, he had the good fortune to come to the United States, where he attended Harvard University to receive his bachelor's degree in 1922, master's in 1925, and Ph.D. in 1926, all in mathematics. He continued post-doctural studies, first at the University of Hamburg, Germany, and then at Princeton University. His natural talent for teaching obtained early expression, first as an instructor at Harvard and then as an associate professor at Grinnell College, Iowa.

In 1930, he joined Humble Oil & Refining Company as a research mathematician in its still new Geophysics Department. In 1936, he was promoted to supervisor in charge of Geophysical Computing. From 1949 to 1954, he held the position of Chief Mathematician. His talents then became available to all segments of the company, including the Departments of Petroleum Engineering, Accounting, Tax, Sales, as well as Geophysics.

In 1954, he was transferred to the Standard-Vacuum Oil Company as consultant and adviser in geophysics, where until his death in 1956, his talents as an ambassador, as well as a mathematical scientist, stood the company in good stead in its working relationships with partners abroad.

As might be anticipated, he was a civilian consultant to the U. S. Navy during War II in the then new field of operations research. He was very well known in professional circles, being a member of the

Mathematical Society, and the
Mathematical Association

also, he was a fellow of the

Geophysical Union, and the
Seismological Society of America

plus being a long-time member of the SEG.

I have presented just the highlights of a wonderful individual, who is represented by our memorial volume, *Lessons in Seismic Computing*. I am honored indeed to represent the Society in trying to express adequate thanks to Mrs. Slotnick for her kind generosity to the Society.

It is also a distinct personal pleasure to give her now a special copy of the Slotnick Memorial Volume, which we all intend as a token of the high regard of the entire exploration industry for her.

This special copy has been inscribed on its outer front cover with the message—

> "Presented to Mrs. M. M. Slotnick by
> the Society of Exploration Geophysicists
> at a meeting of the Houston Geophysical Society
> November 23, 1959"

CECIL H. GREEN

## CONTRIBUTORS

FRANCIS COLLINS

FRANCIS COLLINS studied electrical engineering at Rice Institute, Houston, Texas, receiving a B.S. degree in 1942. For the next four years he worked for Sylvania Electric Products, Inc., first in the radio tube engineering department in Emporium, Pennsylvania, and later in the circuit research laboratory and in the patent department in New York. During part of this period he also attended Stevens Institute of Technology, Hoboken, New Jersey, and was granted the M.S. degree in electrical engineering in 1950.

Since 1946 he has been employed in the Dallas productproduction research laboratory of the Atlantic Refining Company. These years have been about equally divided between theoretical petroleum reservoir engineering and methods for interpreting geophysical measurements. In 1955 the Society of Petroleum Engineers awarded him its Certificate of Service for work in the standardizing of mathematical symbols for reservoir engineering and electric logging. His technical society memberships are: AIME, IRE, EAEG, Dallas Geophysical Society, ACM, SIAM, and SEG.

IRVING FATT

Born: September 16, 1920, in Chicago, Illinois, Married, two children. Education: B.S. in Physical Chemistry, University of California, Los Angeles, M. S. in Physical Chemistry, University of California, Los Angeles, Ph.D. in Physical Chemistry, University of Southern California.

Professional and Academic Experience: September 1957–present, Associate Professor of Petroleum Engineering, University of California at Berkeley; February 1948–September 1957, Senior Research Chemist and Group Supervisor, California Research Corporation, La Habra, California; September 1946–February 1948, Graduate Student and Teaching Assistant, Chemistry Department, University of California, Los Angeles; March 1944–August 1946, Instructor in Radio and Electronics, Air Force Technical School, Yale University.

Memberships and Affiliations: ACS, AIME, AAPG, Phi Lambda Upsilon, Sigma Xi; Technology Committee, AIME, 1957; Chairman, San Francisco Subsection, Society of Petroleum Engineers, 1958–59.

BION H. KENT

BION H. KENT received the B.A. in Professional Geology in 1949 from Cornell University, and the M.S. in General Geology in 1952 from Stanford University. Since 1949 he has been employed by the U. S. Geological Survey as a geologist, with field experience in Alaska, United States, and Mexico. In 1954 he was appointed Division Photogeologic Training Officer at the U. S. Geological Survey regional office at Menlo Park, California. Research and teaching assignments concern the use of aerial photographs and precision photogrammetry in geologic work. In 1958 he was the geologic, technical advisor at the National University of Mexico, as a member of the ICA/Mexico staff.

Mr. Kent is a member of the Geological Society of America and the American Society of Photogrammetry.

W. T. KINOSHITA graduated from the Colorado School of Mines in 1951 where he received a degree in Geological Engineering. In 1957 he did graduate work in geophysics at Stanford University. During the period 1951 to 1953 he served in the U. S. Army in a topographic engineer battalion. Since 1953 he has served as a geophysicist on projects in Cuba, Alaska, and western United States with the U. S. Geological Survey. He is a member of the Society of Exploration Geophysicists and Geological Society of America.

W. T. KINOSHITA

ROBERT L. MANN is an Associate Research Engineer with the Continental Oil Company, Research and Development Department, in Ponca City, Oklahoma. He has just recently joined the Continental Oil Company after receiving an M.S. degree in Petroleum Engineering at the University of California. He was born in Chico, California, May 26, 1931.

Mr. Mann was a naval jet pilot prior to completing his education. He is presently attached to a Naval Air Reserve Squadron at Olathe, Kansas. He is a member of Tau Beta Pi and Sigma Xi.

ROBERT L. MANN

ROBERT M. MOXHAM

ROBERT M. MOXHAM received a B.S. degree in geology from the Ohio State University in 1942. He joined the U. S. Geological Survey the same year. Mr. Moxham was with the Alaskan Branch of the Survey for a period of ten years, his work including geologic studies of copper deposits, radioactive materials and industrial minerals. Since 1952 he has been associated with the Geophysics Branch of the Survey, served as Chief of the Radiation Section and is presently Staff Geologist of the Geophysics Branch.

JOHN D. WINSLOW

JOHN D. WINSLOW was born at Fort Monroe, Virginia, on June 21, 1923. He received his A.B. in geology at Brown University in 1949. A year of graduate study at the University of California at Los Angeles followed. He received his Ph.D. degree from the University of Illinois in 1957.

He has been continuously employed as a geologist with the Ground Water Branch of the U. S. Geological Survey since 1950, except for a period of W.A.E. status while at the University of Illinois (1955–57) and a second period of W.A.E. status while engineering geologist of the Indiana Geological Survey (1958–59). His principal work has been in hydrogeology and engineering geology.

Dr. Winslow is a member of the American Geophysical Union, the Geological Society of America, the American Association of Petroleum Geologists, the Society of Economic Paleontologists and Mineralogists, the International Association of Hydrogeologists, the American Association for the Advancement of Science, the Ohio Academy of Science, and Sigma Xi.

Biographies of the following authors appear in the earlier issues of GEOPHYSICS as follows: F. A. Angona, v. 23, p. 596; T. C. Richards, v. 23, p. 380; George Shumway, v. 23, p. 600; R. H. Warrick, v. 21, p. 510.

# SOCIETY ROUND TABLE

## COMMITTEES FOR THE YEAR ENDING IN NOVEMBER 1960

### EXECUTIVE COMMITTEE

*President:* T. O. HALL, General Geophysical Company, Houston, Texas
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*Vice-President:* DEAN WALLING, Western Geophysical Co. of America, Los Angeles, California
*Secretary-Treasurer:* PHIL P. GABY, Consultant, Jackson, Mississippi
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*Past President:* E. V. MCCOLLUM, E. V. McCollum & Company, Tulsa, Oklahoma

**Nominations**
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E. V. MCCOLLUM
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(To be appointed)

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(Committee to be appointed)

**American Geological Institute Directors**
(To be appointed)

**AGI Glossary**
(To be appointed)

**AGI Committee on Licensing**
(To be appointed)

**AAAS Council Representative**
CHARLES W. OLIPHANT

**Distinguished Lectures**
J. W. THOMAS ('60), *Chairman*
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**Safety**
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**Mining Geophysics**
STANLEY H. WARD, *Chairman*
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JACKSON YOUNG, *Chairman*
(Committee to be appointed)

**Publicity**
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J. A. PEOPLES

**Radio Facilities**
(To be appointed)

**Research**
J. P. WOODS, *Chairman*
(Committee to be appointed)

### LOCAL SECTIONS

**Ark-La-Tex Geophysical Society (6),** Shreveport, La., chartered March 12, 1949, officers elected in May. *Meetings:* Monthly, last Monday, noon luncheon ($1.50), Captain Shreve Hotel.
Virgil Teufel, *pres.*
J. A. Boydstun, *v-pres.*
R. H. Wardell, *secty-treas.*, Western Geophysical Co., 322 Fairfield Bldg., Shreveport, La.

**Canadian Society of Exploration Geophysicists (9),** Calgary, Alta., chartered January 24, 1952, officers elected in February. *Meetings:* Monthly, no set schedule.
H. J. Kidder, *pres.*
M. B. Dobrin, *v-pres.*
P. J. Savage, *secty-treas.*, Nance Exploration Co., Condon Bldg., Calgary, Alta.

**Casper Geophysical Society (11),** Casper, Wyoming. Chartered May 23, 1953, officers elected in May. *Meetings:* Monthly, 1st Monday, 7:00 P.M., dinner ($2.75), Townsend Hotel, Casper, Wyoming.
G. L. Ellis, *pres.*
B. A. Tuller, *v-pres.*
Robert Davenport, *secty-treas.*, Wyoming Seismograph Co., Box 631, Casper, Wyoming.

**Coastal Bend Geophysical Society (24),** Corpus Christi, Texas, chartered May 29, 1959, officers elected in May.
Walter Pfennig, *pres.*
J. W. Bolinger, *v-pres.*
James Vetters, *treas.*
B. C. Johnson, *secty.* Forest Oil Corp., Box 1356, Corpus Christi, Texas.

**Cochabamba Geophysical Society (23),** Cochabamba, Bolivia, chartered May 4, 1959, officers elected in December.
R. H. Matthews, *pres.*
Charles W. Hyall, *v-pres.*
Noel C. Manning, *secty.-treas.*, Geophysical Service Inc., Casilla #1437, Cochabamba, Bolivia.

**Dallas Geophysical Society (4),** Dallas, Texas, chartered August 7, 1948, officers elected in December. *Meetings:* Monthly, usually 2nd Monday, 8:00 P.M., Fondren Science Bldg., Southern Methodist University.
H. F. Dunlap, *pres.*
E. F. McMullin, *1st v-pres.*
M. S. Hathaway, *2nd v-pres.*
W. B. Heroy, Jr., *secty-treas.*, Geotechnical Corp., Box 28277, Dallas 28, Texas.

**Denver Geophysical Society (8)**
*Meetings:* Monthly, 1st Monday, 5:30 P.M., dinner at 7:00 P.M. ($3.00), Petroleum Club, Denver.
John C. Hollister, *pres.*
Arthur W. Black, *v.-pres.*
Charles E. McMunn, *secty-treas.* Tower Exploration Inc., P.O. Box 156, Englewood, Colorado.

**Geophysical Society of Edmonton (22),** Edmonton, Alta., Canada, chartered March 20, 1959, officers elected in December.
A. S. Gibson, *pres.*
R. F. Keller, *v-pres.*
R. D. Jacques, *secty-treas.*, Mobil Oil of Canada, Ltd., Financial Bldg., Edmonton, Alta.

**Fort Worth Geophysical Society (5)**
O. A. Strange, *pres.*
R. H. Dana, *v.-pres.*
U. A. Rowe, *secty.*
C. H. Thurber, *treas.*, Champlin Oil and Refining Co., Box 9365, Forth Worth, Texas.

**Four Corners Geophysical Society (19),** Durango, Colo., and Farmington, N. M., chartered June 19, 1958, officers elected in May.
J. P. Badami, *pres.*
F. E. Endacott, Jr., *1st v-pres.*
J. F. Wright, *2nd v-pres.*
G. D. Sindorf, *treas.*
L. E. Schneider, *secty.*, Empire Geophysical, Inc., Box 1484, Durango, Colo.

**Geophysical Society of Houston (2),** Houston, Texas, chartered February 14, 1948, officers elected in May. *Meetings:* Monthly, noon luncheon.
D. P. Carlton, *pres.*
S. P. Worden, *1st v-pres.*
K. A. Webb, *2nd v-pres.*
S. M. Pena, *treas.*
J. L. Bible, *secty.*, 1045 Esperson Bldg., Houston 2, Texas.

**Jackson Geophysical Society (15)**
Joel Macgregor, *pres.*
John Babb, *v-pres.*
Thomas Tillman, *secty.-treas.*, Sun Oil Co., P.O. Box 850, Jackson, Miss.

**Montana Geophysical Society (14),** Billings, Mont., chartered April 12, 1954, officers elected in December. *Meetings:* Monthly, 2nd Monday, 7:30 P.M., Billings Petroleum Club.
W. H. Dawson, *pres.*
R. H. Mansfield, *1st v-pres.*
F. J. Felice, *2nd v-pres.*
Max Judy, *secty.-treas.*, Sun Oil Co., Box 1896, Billings, Mont.

**New Mexico Geophysical Society (18),** Roswell, N. M., chartered September 18, 1957, officers elected in May.
R. E. Lawson, *pres.*
Delmer M. Woods, *1st v-pres.*
T. E. Daly, *2nd v-pres.*
H. C. Ives, *secty.-treas.*, Atlantic Refg. Co., Box 6640, Roswell, N. M.

**Geophysical Society of Oklahoma City (10),** Okla. City, Okla., chartered September 30, 1952, officers elected in May. *Meetings:* Monthly, 2nd or 3rd Monday.
A. J. Oden, *pres.*
C. L. Howell, *1st v-pres.*
H. J. Fenton, *2nd v-pres.*
W. S. Hart, *treas.*
E. M. Peacock, *secty.*, Sohio Petroleum Co., 1606 N. Broadway, Oklahoma City, Okla.

**Pacific Coast Section (3),** luncheon ($2.75) Rodger Young Auditorium, Los Angeles.
F. F. Lambrecht, *pres.*
Nolan A. Webb, *v-pres. S.D.*
M. C. MacMurrough, *v-pres.*
Fred G. Knight, *v-pres. N. D.*
Tom Slaven, *secty.-treas.*, Western Geophysical Co. of America, 523 W. 6th St., Los Angeles, Calif.

**Permian Basin Geophysical Society (7),** Midland, Texas, Chartered January 30, 1950, officers elected in December. *Meetings:* Monthly, 2nd Tuesday, 7:30 P.M., Midland Women's Club.
J. E. Clark, *pres.*
E. E. Fickenger, *1st v-pres.*
B. H. Hinton, *2nd v-pres.*
S. T. Miller, *treas.*
L. M. Scofield, *secty.*, Burton Exploration Co. Inc., 4513 W. Storey, Midland, Texas.

**Regina Geophysical Society (22)**
A. C. Armstrong, *pres.*
B. F. Fulton, *v-pres.*
J. R. Muir, *secty.-treas.*, The California Standard Co., 1836 Smith St., Regina, Saskatchewan, Canada.

**Geophysical Society of South Texas**
J. W. E. Edmonson, *pres.*
P. J. Rudolph, *v-pres.*
Donald W. Jones, *secty.-treas.*, Sun Oil Co., 832 Milam Bldg., San Antonio, Texas.

**Southeastern Geophysical Society (13),** New Orleans, La., chartered April 1, 1954, officers elected in January. *Meetings:* Monthly, 3rd Monday, noon luncheon ($1.50), St. Charles Hotel.
George Morgan, *pres.*
J. T. McMaster, *1st v-pres.*
D. R. Scheel, *2nd v-pres.*
O. J. Rauschenbach, *secty.-treas.*, Continental Oil Co., 414 Carondelet Bldg., New Orleans 12, La.

**Southwest Louisiana Geophysical Society (16),** Lafayette, La., chartered January 4, 1956, officers elected in December.
Jack Wallner, *pres.*
Walter Hurt, *1st v-pres.*
Richard Hollenbaugh, *2nd v-pres.*
Ned Pratt, *treas.*
Lucius Geer, *secty.*, Union Oil of California, Box 1224 OCS, Lafayette, La.

**Geophysical Society of Tulsa (1)**
K. S. Cressman, *2nd v-pres.*

**Utah Geophysical Society (17)**
L. D. Oster, *pres.*
K. L. Cook, *1st v-pres.*
H. H. Nuttli, *2nd v-pres.*
D. J. O'Halloran, *secty.-treas.*, Standard Oil of California, P.O. Box 1076, Salt Lake City, Utah.

**Asociacion Venezolana de Geofisica (21)**
W. J. Pfeffer, *pres.*
D. F. Warner, *1st v-pres.*
A. P. Seifert, *2nd v-pres.*
D. W. Danz, *treas.*

## STUDENT SOCIETIES AFFILIATED

**Colorado School of Mines Society of Student Geophysicists**
Joseph R. Anzman, *secty.* Department of Geophysics, Colorado School of Mines, Golden, Colorado.
*Meetings:* Monthly, 2nd Monday, 4:00 P.M.

**Geophysical Society of Saint Louis University**
Norman J. Guinzy, *secty.* 410 Vandalia, Collinsville, Illinois.
*Meetings:* Monthly, 2nd Wednesday 7:30 P.M., meeting only, Institute of Technology.

**SEG Houston Student Section**
Billie Gail Dopslauf, *secty.* 2121 Hollister, Houston, Texas

**University of Toronto Geophysical Society**
B. R. Krause, *secty.* 502 Gilbert Ave., Apt. 107, Toronto, Ont., Canada

**University of Tulsa Student Geophysical Society**
Fred D. Munzlinger, *secty.* Department of Geophysics, 600 South College, Tulsa, Oklahoma.
*Meetings:* Weekly, Thursday, 4:00 P.M., Petroleum Science Bldg.

**Trans-Pecos Student Section**
El Paso, Texas

**Pennsylvania State University Geophysical Society**
Wm. R. England, *secty.* College of Mineral Industries, University Park, Pa.
*Meetings:* to be announced.

**University of Utah Geophysical Society**
James D. Morgan, *secty.* College of Mines and Mineral Industries, Salt Lake City 1, Utah.
*Meetings:* Monthly, 1st Thursday Noon, Mines Building. Other special meetings to be announced.

**A & M College of Texas Student Geophysical Society**
Edward C. Hanson III, *secty.* Geology and geophysics dept., A & M College of Texas, College Station, Texas.

# SOCIETY AFFILIATIONS

**American Association for the Advancement of Science**

*SEG is affiliated under Section E, Geology and Geography*
1515 Massachusetts Avenue
Washington 5, D. C.
Paul E. Klopsteg, *President*
Paul A. Scherer, *Treasurer*
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*A Cooperative relationship*
Box 979
Tulsa 1, Oklahoma
L. G. Weeks, *President*
A. H. Bell, *Vice-President*
H. T. Morley, *Secretary-Treasurer*
G. E. Murray, *Editor*
G. S. Buchanan, *Past President*
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*SEG is a charter member society*
2101 Constitution Ave., N.W.
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Donald H. Dow, *Secretary-Treasurer*
R. C. Stephenson, *Executive Director*

**European Association of Exploration Geophysicists**

*Mutually affiliated*
30, Carel Van Bylandtlaan
The Hague, Netherlands
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V. Baranov, *Vice-President*
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**Petroleum Exploration Society of Libya**

*Mutually Affiliated*
P. O. Box 900
Tripoli, Libya
Sam Frazier, *President*

## MEMBERSHIP APPLICATIONS RECEIVED

Applications for active membership have been received from the following candidates. This publication does not constitute an election but places the names before the membership at large, in accordance with Bylaws, Article III, Section 4. References are listed in parentheses following the names of each candidate. If any member has information bearing on the qualifications of these candidates he should send it to the president within thirty days.

### APPLICATIONS FOR ACTIVE MEMBERSHIP

John McGregor Andrews (C. L. Schroll, T. J. Mouche, J. C. Hoffman & F. J. Habr)
John Derland Baker (H. W. Stoneman, C. N. Hurry, R. C. Clark & M. Romberg)
George R. Barrett (S. A. Teasley, J. W. Bolinger, R. G. Wells & J. G. Thompson)
Rene Bolusset (R. Bouchon, M. Lepetit, M. Pieuchot & A. Clement)
Luigi Carissimo (T. Rocco, U. Colledan & R. Cassinis)
James Worn Champion (T. O. Harkness, G. W. Conrad & H. M. Blevins)
Pol. Claude Chapuis (H. L. Brewer, F. D. Nichol, R. A. Drash & A. Frey)
Don Morse Clark (J. A. Long, P. J. Rausch, R. A. Peterson & M. Slavin)
John H. Clements (C. Sappington, J. S. Spencer & K. Webb)
Manuel I. Del Rio (J. F. Wright, J. W. Rogers, D. T. McCreary & J. C. Yeager)
Harry Robinson DeVinna (L. B. Tromblo, H. B. Mayo, W. Baird & W. H. Hawkes)
Marshall Woodworth Dweis (A. E. Pallister, G. F. Coote & G. R. Haun)
Zbigniew Jozef Fajklewicz
Robert George Graf (L. E. Whitehead, B. Vorheis, R. P. Barnes & B. F. Howell, Jr.)
Oliver Edward Gregson (R. F. Hughes, H. H. Moody, J. W. Fetrow & W. B. Goodenow)
Elbert Allen Grimsley (O. W. Anderson, J. E. Harrison, E. Thomsen & R. W. Walling)
Harold Huston Harvey (G. R. Perkins, R. L. Winchell, C. J. Quinn & G. D. Gibson
David Johnston (R. C. Powell, J. A. Adams, C. H. Savit & T. D. Sinclair, Jr.
William C. Knudsen (F. G. Blake, L. P. Stephenson, S. H. Yungul & N. A. Riley)
George E. Kramer (G. D. Causey, G. M. Roberts & J. O. Sims)
Joe Pat Lindsey (J. E. Bondurant, H. C. Johnsen & R. G. Piety)
William Harold Lucas (R. J. Hope, T. O. Hall, C. Sappington & J. S. Spencer)
Wendell H. Merrill (A. J. Christman, A. McClung, R. H. Howe & K. A. Waters)
Calvin Duane Nelson (A. E. Pallister, G. F. Coote, G. R. Haun & G. A. Thompkins)
Lawrence C. Nelson (A. M. Field, G. E. Noble, G. W. Isensee & W. M. Tottenham)
Miles Dillon Nunnally (B. H. Hinton, A. A. Hunzicker & K. A. Webb)
Lewis Lee Oriard (V. J. Blum, C. Kisslinger, R. Heinrich & O. Nuttli)
Emilio Pacchiarotti (T. Rocco, U. Colledan & L. Baulino)
Donald Vernon Parker (C. J. Frankovitch, N. H. Miller & D. D'Arcy)
George Podolsky (H. V. W. Donohoo, C. Fogarty, D. Salt & D. Sutherland)
Robert L. Schulze (R. Hope, T. O. Hall, C. Sappington & J. S. Spencer)
Langdon Smith (O. L. Taylor, G. H. Westby, J. W. Hammond & A. J. Barthelmes)
Emir Luis Tavella (J. V. Price, D. W. Rockwell & J. F. Fuller)
Dennis Lynn Troth (J. A. Barthelmes, J. N. Wilson, J. W. Hammon & R. W. Saubert)
James Leo Waddell (G. L. Laird, A. P. Marsh, D. Woods & R. W. Thompson
William S. Weber (C. N. Yancey, E. R. Brumbaugh, R. C. Kendall & F. R. Versaw)
Sam P. Wildman (T. O. Hall, C. Sappington, R. J. Hope & J. S. Spencer)
William Richard Wolfe (E. M. Peacock, H. B. Mayo, L. B. Trombla, R. H. Glover & W. Baird)
Herman Judson Wyatt (H. C. Talley, Jr.. R. F. Bennett, J. Bemrose & C. C. Sellers, Jr.

### APPLICATIONS FOR TRANSFER TO ACTIVE MEMBERSHIP

Richard Carl Anderson (G. J. Hulsewe, G. A. Howard, R. H. Rainey & C. M. Moore)
Joseph Wilbur Berg, Jr. (B. F. Howell, Jr., C. B. Officer & G. V. Keller)

Malcolm K. Brachman (E. E. Van Petten, S. M. Leventhal, R. B. Hohlt & F. J. Agnich)
John D. Closs (C. T. Spalding, C. B. Scott, M. E. Lamkin & M. E. Wimber)
Arthur Tom Cobb (F. L. Searcy, L. E. Whitehead, E. L. Mount & D. S. Godshalk)
Jerry Hicks Collins (J. C. Lusk, A. S. Maureira, J. A. Standridge & W. McKinley)
Elwood M. Cottle (R. L. Zieve, W. H. Hawkes, G. L. Ellis & H. A. Willis)
John Donald Thomas Crane (H. J. Kidder, D. V. Bigelow, L. Castelli & C. E. Dalik)
Jay B. Dreves (S. S. Giezandanner, C. R. Wallace, T. L. Kunkel & L. W. Cobena)
Fay Lewis Eaton, Jr. (W. H. Dawson, W. E. Martin, J. P. Duncan & C. T. Phillips)
Howard Ray Ellard (C. J. Chapman, L. F. Kealing, R. J. H. Smith & C. H. Acheson)
Joseph H. Evens (O. A. Seager, I. J. Reed, S. Zimerman & J. H. Hoke)
Charles P. Felix (J. Baade, J. B. Parkhill & D. K. Kirk)
Wilfred Douglas Francis (C. B. Stone, H. P. Coster, O. B. Manes & R. C. Hilton)
Janes Eugene Froelich, Jr. (K. G. McCann, A. Pegues & W. L. Audas)
Charles LaVerne Funk (J. D. Marr, W. H. McKelvy, W. S. Hawes & T. F. Dupont)
George David Garland (E. V. McCollum, R. J. Watson, C. Green & W. Erdahl)
Teddy J. Greer (C. W. Blakey, B. F. Rummerfield, J. Bentley-Llewellyn & E. H. Weltsck)
William H. Guyton (J. M. Murphy, S. A. Spencer, P. M. McNally & W. H. Courtier)
Henry J. Hajovsky (R. M. Low, H. L. Ehrardt, R. M. Rogers & K. D. Kubik)
Frank E. Halpenny (H. J. Kidder, D. V. Bigelow, L. Castelli & C. E. Dalik)
Wilfred P. Hasbrouch (R. C. Holmer, J. R. Hayes, G. T. Merdeth & J. C. Hollister)
Gordon T. Heine (B. F. Rummerfield, E. H. Weltsch & J. T. Woodburn)
John Douglas Laker (T. O. Hall, C. Sappington, J. S. Spencer & R. J. Hope)
Barry R. Lundy, Jr. (P. I. Bediz, J. L. Robinson, B. F. Rummerfield & J. L. Poole)
Howard Stuart McColl (S. W. Fruehling, D. B. McDougall, P. S. Stoutjesdyk, T. B. Portwood)
Donald R. Mabey (G. D. Bath, M. F. Kane & L. C. Pakiser, Jr.
James Warner Mitchell (E. D. Gaby, J. H. Babb, R. L. Schmidt & J. McGregor)
Wilfred C. Mosier (S. C. Stoneham. M. C. MacMurrough, B. F. Grossling & C. A. Bengston)
Arthur F. Oestmann (R. P. Warren, C. S. Fleischmann, A. A. Moore, Jr., & J. R. McMahan, Jr.
Charles Edward Randall (O. W. Anderson, J. E. Harrison, R. W. Walling & E. Thomsen)
Kenneth V. Radic (D. W. Beddo, G. L. Ellis)
James Clifford Rees
Paul S. Roberts (J. P. Badami, A. W. Black, C. M. Ferree & L. E. Whitehead)
Alexander Sabitay (E. J. Malovich, G. A. Howard, K. E. Burg & J. C. Hollister)
Edwin G. Smith (A. A. Milton, R. W. Mossman, P. E. Goodwin & R. L. Whitaker)
William C. Stroup, Jr. (E. L. Erickson, D. E. Fickinger, H. Evans, Jr., J. Setters)
De Troy Trammell (L. McCraney, B. L. Bass, W. H. Smith & H. W. Gibson)

## NOMINEES FOR THE 1960–1961 EXECUTIVE COMMITTEE

The following biographical sketches are presented to acquaint members of the Society with nominees appearing on the official ballot which will be mailed to all active members in good standing in June. Bylaws Article VII, Section 4, provides that "Prior to June 1, nominations in writing, signed by at least twenty honorary members or active members in good standing and accompanied by the written consent of the candidate, may be submitted to the President."

A. E. McKay

A. E. "Sandy" McKay, candidate for President, received his B.S. degree from the University of Oklahoma in 1928. Upon graduation he joined The Indian Territory Illuminating Oil Company (now Cities Service) as a Magnetometer operator, served in subsurface, surface, core drill, and land positions until the Spring of 1933 when he entered seismic operations where he progressed through all positions to the position of Seismic Supervisor.

In 1937 he joined The Atlantic Refining Company as Co-ordinator of Geophysics and Seismic Supervisor, a position he held until given leave of absence to serve, from April, 1942 until September, 1944, as a Major in the U. S. Air Force. Upon release from the services he returned to Atlantic as Assistant Chief Geophysicist, resigning in 1950 to form the Continental Geophysical Company where he serves as President of the firm. He is a Vice-President of NAMCO, International, Inc., an association of domestic geophysical companies joined together for world wide geophysics.

Mr. McKay has been a member of the Society of Exploration Geophysicists 22 years, the American Association of Petroleum Geologists 30 years, and is a member of the European Association of Exploration Geophysicists, American Association for Advancement of Science, Texas Academy of Science, Fort Worth Geophysical and Geological Societies, and the Dallas, Houston and Oklahoma City Geophysical Societies. He served as the first President of the Dallas Geophysical Society when it was formed in 1947 and was President of the Fort Worth Geophysical Society in 1956. He has served as SEG Representative and on various committees with SEG and AGI. Published articles have appeared in "Geophysics" and in "Geophysical Case Histories."

J. P. Woods, Candidate for President, graduated from the University of Texas in 1925 with the degree of B.S. in Electrical Engineering. He received the M.S. degree in 1930 and a Ph.D. in Physics in 1932 from the same University. From 1933 to 1940, he was in the Geophysical Laboratory of the Shell Oil Company. From 1941 to 1944, he was in the Radio Research Laboratory of Harvard University. Since 1944, he has been Director of the Geophysical Laboratory of The Atlantic Refining Company.

Dr. Woods is a member of the Society of Exploration Geophysicists, the American Association of Petroleum Geologists, the Dallas Geophysical Society, the European Association of Exploration Geophysicists, the American Geophysical Union, and the Seismological Society of America. He is Past President of the Dallas Geophysical Society and a past Vice-President of the Society of Exploration Geophysicists. He has been Chairman of the S.E.G. Publications Committee, and is now Chairman of the S.E.G. Research Committee.

J. P. Woods

JOHN C. HOLLISTER, Candidate for First Vice-President, has been head of the department of Geophysical Engineering at the Colorado School of Mines since September, 1949. At that time he left Heiland Research Corporation (now the Heiland Division of Minneapolis-Honeywell), where he served as Vice-President and General Manager, to return to Mines, his Alma Mater (class of 1932).

Professor Hollister attended the University of Oregon before transferring to Mines in 1929. He joined Plains Exploration Company in 1932, as a geophysical engineer, leaving in 1934 to become co-founder of the Heiland Company.

He is a member of Tau Beta Pi, Society of Exploration Geophysicists, A.I.M.E., American Geophysical Union, European Association of Exploration Geophysicists, and Denver Geophysical Society. He has served as Secretary-Treasurer and on various committees of SEG, as an Associate Editor of GEOPHYSICS, and as President of the Denver Society.

JOHN C. HOLLISTER

WALTER B. LEE

WALTER B. LEE, (JR.), a candidate for First Vice-President, began his higher education at Texas A. & M. College in 1927 in Civil Engineering. He transferred to the University of Texas in the fall of 1929.

He joined Gulf Research & Development Company in the fall of 1931 as an assistant interpreter on Gulf Oils' first company operated seismograph party. Since that time he has worked as Party Manager, Party Chief and Supervisor in Texas, Louisiana, Mississippi, Oklahoma, California and Old Mexico and received training at various times at Gulf's Research Laboratories near Pittsburgh, Penn. In 1950 he became Supervisor of Gulf's Geophysical Operations in the South-Southeast U. S. A. He transferred to Gulf Oil Corporation in mid-1954 and since that time has been Supervisor of Geophysical Operations for its Houston Production Division.

Lee is an active member of the Society of Exploration Geophysicists, the Geophysical Society of Houston and the Houston Geological Society. He is currently Vice-Chairman of the Houston Geophysical Club. He has served the Geophysical Society of Houston as Treasurer and as President and is at present General Chairman for the National SEG Convention to be held in Galveston, Texas during November, 1960. He has served, since 1955, on a special API committee compiling a manual on Safe Practices in Geophysical Exploration Operations.

FLINT AGEE

FLINT AGEE, Candidate for Vice-President, graduated from the University of California at Los Angeles in 1933 with an AB degree in geology.

After a brief period with a drilling company, he joined the Western Geophysical Company in 1934 where he gained experience in various field party positions in California and the Mid-Continent.

In 1935, Flint was appointed Party Chief on the first field party of the National Geophysical Company. He remained with National as a Partner, Party Chief, and Supervisor until 1945.

He has been with the United Geophysical Corporation since 1945 serving as Party Chief, Supervisor, and Area Manager. Flint is now a Vice-President and Manager of North American Operations for United.

Flint has been active in the Pacific Section of S.E.G. as Representative (1956), Vice-President (1951), and President (1957).

He was General Chairman of the Convention Committee for the 29th Annual International Meeting of the Society of Exploration Geophysicists in 1959 at Los Angeles, California.

He is a member of the Society of Exploration Geophysicists and the American Association of Petroleum Geologists.

ROBERT C. KENDALL

ROBERT C. KENDALL, candidate for Vice-President, was born in Jeffersonville, Indiana on January 24, 1911 where he received his primary and high school education. He holds a B.A. from DePauw University and a M.S. from California Institute of Technology, both in Physics. He joined Shell Oil Company as a field seismologist in Long Beach, California, in September 1936. He was promoted to seismologist Party Chief in January 1939 and continued in that capacity on field crews in California, northern Texas and southern Oklahoma for the next six and one-half years. He was assigned to Shell's Tulsa Area office in July 1945 as a Seismic Supervisor and was appointed Area Geophysicist in 1947. He was transferred as Area Geophysicist to Shell's newly formed Denver Area in the fall of 1953 and has continued in that capacity to the present.

Mr. Kendall served as Secretary of the Tulsa Geophysical Society, as Vice-President and President of the Denver Geophysical Society, is presently District Representative for the Denver Society and Chairman of the SEG Scholarship Administration Committee.

GEORGE D. GARLAND

GEORGE D. GARLAND, Candidate for Secretary-Treasurer, graduated from the University of Toronto in engineering physics in 1947, received his M.A. in geophysics from that institution, and his Ph.D., also in GEOPHYSICS, from St. Louis University.

Following his return to Canada, he lectured at Toronto from 1949 to 1952, then joined the staff of the Dominion Observatory, Ottawa, as a research geophysicist. In this capacity, he carried out geophysical studies, chiefly gravimetric and magnetic, over various types of geological structures in Canada, and also worked on the establishment of a primary gravity calibration line between Mexico and Alaska.

In 1954 he came to the University of Alberta, to set up a teaching and research program in GEOPHYSICS. The research projects of the Alberta group now include studies on gravity, earth currents and magnetic pulsations, age determinations of rocks, and geothermometry.

Dr. Garland was a charter member and first President of the Geophysical Society of Edmonton, which was incorporated as a local section of the S.E.G., and he is currently its District Representative on the S.E.G. council. He is a member of the Geophysics Committee of the National Research Council of Canada, and Editor of its publication, "The Canadian Geophysical Bulletin," and is an Associate Editor of the Journal of Geophysical Research. In addition to the S.E.G., in which he has held membership in various grades since 1947, he is a member of the American Geophysical Union and a Fellow of the Royal Society of Canada.

FRANCIS A. HALE

FRANCIS A. HALE, a candidate for Secretary-Treasurer, was born in Woonsocket, Rhode Island, on November 28, 1911.

He received the Bachelor of Arts Degree in 1934 and the Master of Arts Degree in 1936 from the University of Texas, both degrees being in Physics.

From 1936 to 1946 he was employed by Geophysical Service Incorporated, serving as Computer and Party Chief in Louisiana, Texas and California. Since 1946 he has been employed in subsidiaries of the Standard Oil Company of California. He spent four years as a seismologist with Richmond Exploration Company in Venezuela and a brief period at California Research Corporation, La Habra, California. He has been Chief Geophysicist of The California Standard Company, Calgary, Alberta, since 1951.

In S.E.G., Mr. Hale was a member of the Public Relations Committee in 1956–57 and was a District Representative from the Canadian Society of Exploration Geophysicists for the two-year term 1956–1958. He was President of the Canadian Society of Exploration Geophysicists in 1958–59 and continues to serve on the Executive Committee of this local section as a Past President.

Mr. Hale is an Associate Member of the American Association of Petroleum Geologists, a Member of the Alberta Society of Petroleum Geologists, and the Association of Professional Engineers of Alberta.

# ANNOUNCEMENTS

## INSTITUTE FOR SCIENCE TEACHERS

A grant of $129,900 for the purpose of conducting a summer institute for high school teachers of science and mathematics has been made to Western Reserve University by the National Science Foundation it was announced by University President John S. Millis.

WRU received a grant of $128,600 for the same purpose last year.

Director of the summer institute scheduled to run for 11 weeks beginning June 20th will be Dr. Ralph Petrucci, assistant professor of chemistry at WRU. The institute will be divided into two sessions of six and five weeks.

Teaching participating in the institute will receive stipends and no fees or tuition will be charged by the University.

Applications must be postmarked by Feb. 15 in order to be considered while all initial stipend offers have until April 1 to accept or decline. Election of participants will be based on the capacity of the applicant to develop as a teacher and to profit from the program.

Teaching staff of the institute will be chosen from outstanding scientists and teachers from the WRU faculty and from other institutions.

Objectives of the summer institute will be: to improve subject-matter competence of the participating teachers; to strengthen the capacity of these teachers for motivating able students to consider careers in science; to bring these teachers into personal contact with prominent scientists who participate in the institute, with a view to stimulating the interest of the teachers and increasing their prestige professionally; and to effect greater mutual understanding and appreciation of each other's teaching problems among teachers of science and mathematics at both the high school and college levels.

Participation in the institute will not be limited strictly to teachers receiving stipends.

## ROCK MECHANICS SYMPOSIUM

The proceedings of the Third Annual Rock Mechanics Symposium, held at the Colorado School of Mines, April 20 through 22, have been published as a CSM Quarterly.

The Symposium, supported by a $2,500 National Science Foundation grant this year, was cosponsored by Mines, the University of Minnesota and Pennsylvania State University. More than 300 industrial and research engineers and educators attended the conference and heard papers presented by outstanding engineers and scientists from five nations.

The Symposium was divided into four major sections, each dealing with a distinct area of rock mechanics. They treated nuclear blasting, geophysics, soil and rock mechanics factors, and common underground and explosive failures.

The 370-page publication, Volume 54, number 3, is priced at $3. It is available from the Department of Publications, the Colorado School of Mines, Golden.

## GEOPHYSICS FELLOWSHIP GRANTED

Robert P. Quitzau of Bellmore, N. Y., has been selected by the University of Utah as the recipient of the Pan American Petroleum Foundation fellowship in geophysics for the 1959–60 academic year.

The announcement was made by C. L. Larson, Jr., vice president of the foundation and vice-president and Rocky Mountain division manager of Pan American Petroleum Corp., which created and is supporting the foundation.

Mr. Quitzau, a 1955 graduate of Colgate University, Hamilton, N. Y., holds a B.A. degree in geology from Colgate. On the basis of his academic record, he was elected to Phi Beta Kappa honorary society. His scholastic achievements also won him recognition as a New York State Regents Scholar, Colgate War Memorial Scholar, Geo. Westinghouse Science Achievement Scholar, and the winner of the President's Cup.

At the University of Utah, Mr. Quitzau will study for his master's degree in petroleum geophysics, and later for the Ph.D. degree in the same field. While his specific research project has not yet been determined, his work will be under the direction of Dr. Kenneth L. Cook of the Utah faculty.

## AAPG-SEPM ANNUAL MEETING

"Go east young man" is the slogan of the Geological Society of Washington as hosts to the 45th Annual Meeting of the American Association of Petroleum Geologists in Atlantic City, April 25–28, 1960. One hundred years ago when Colonel Drake completed his famous oil well at Titusville, the youth of the country were fired by Horace Greeley's famous words, "Go west young man."

The tide of oil exploration which started in Pennsylvania a century ago swept westward on the crest of new discoveries. As a result the petroleum possibilities of the Appalachians and the Atlantic Coastal Plain, although attacked spasmodically have never stimulated a major exploration play.

In inviting the petroleum geologists to "go east" in April 1960, the Geological Society of Washington is scheduling four pre-meeting field trips to provide a cross-section of classic Appalachian geology and an opportunity to study Coastal Plain sediments.

The headquarters hotel will be the Chalfonte-Haddon Hall on the famed Boardwalk in Atlantic City and the General Sessions will be held in the Steel Pier Auditoruim out over the water of the Atlantic Ocean. It has been observed that this is probably the first off-shore annual meeting of the AAPG-SEPM.

Meeting with the AAPG will be the Society of Economic Paleontologists and Mineralogists. The SEPM Research Committee is sponsoring a provocative symposium, "The Paleontological and Mineralogical Evidence for Polar Wandering and Continental Drift." Featuring the geology and petroleum geology possibilities of the region will be the symposium on the "Sedimentary and Tectonic Framework of the Atlantic Coastal Region." "Petroleum Geochemistry" and the "Geometry of Sandstone Bodies" will be two general interest symposia. A special feature of the 1960 meetings will be a symposium on "The Mohole." There will be a number of sessions of general interest.

The social calendar will feature an ice breaker cocktail party and an authentic Hawaiian luau. For the ladies there will be tours to historic Philadelphia and to the famed Henry Francis duPont Winterthur Museum and gardens.

The meeting will be topped off by extension trips to Washington where visiting petroleum geologists will have the choice of three guided tours of the Beach Erosion Board, the David Taylor Model Basin and the U. S. Geological Survey, Topographic Division, Atlantic Region. There are also the National Museum and many other interesting spring-time sightseeing features for those who wish a change of pace from technical matters.

Saving the best until last, the famed Pick and Hammer Club of Washington will lampoon the "Mr. Bigs" of the AAPG in a special production. The Pick and Hammer Show will climax the week's activities.

## GEOPHYSICS CUMULATIVE INDEX 1954 THROUGH 1959

A supplementary Cumulative Index of the issues of GEOPHYSICS for the 6-year period 1954 through 1959, as well as of the SEG Geophysical Case Histories, Volume II (1956), is now being compiled by Dr. Kenneth L. Cook, Professor of Geophysics and Head of the Department of Geophysics, University of Utah, Salt Lake City, Utah. The Index will also include the list of patents for this period as compiled by Mr. O. F. Ritzmann, Physicist, Gulf Research and Development Co., Pittsburgh, Pa. The format for the new supplementary index will be identical to the one published in 1955 for the years 1931 through 1953, and will comprise offset printing from Flexoprint cards. The key subject indices will be identical to those used previously, except that a few new ones will be added. To anyone interested in improving the Supplementary Cumulative Index, Dr. Cook requests that he write him prior to July 1, 1959 and offer suggestions as to additional key subject index words or changes in current usage of key subject index words.

(*Left to Right*) H. J. KIDDER, President, Canadian Society Exploration Geophysicists; JOHN BAXENDALE, Co-Chairman, Tournament Committee; BILL DAVIDSON, Sales Manager, Herb J. Hawthorne Inc., Houston, presenting Hawthorne Trophy to the Winner; LES VYE, winner of "Doodlebug" Championship Flight; E. V. MCCOLLUM, President SEG, holding the "Doodlebug" ceramic which went to the winner along with trophy and prize; NORMAN J. CHRISTIE, Chairman, Tournament Committee.

## SEVENTH ANNUAL CSEG GOLF TOURNAMENT

The seventh annual "Doodlebug" golf tournament was held at Banff, Alberta, September 11th, 12th and 13th and as in previous years it was an outstanding success. Sponsored by the Canadian Society of Exploration Geophysicists it drew 180 geophysicists from Western Canada as well as from many points in the United States. The committee was delighted to see so many lady "doodlebugs" in attendance. Special entertainment was planned for the ladies, including a spectacular ride on the new Gondola Lift to the top of Sulphur Mountain.

Mr. Les Vye, Farney Exploration Company Limited, was declared winner of the "Doodlebug" Championship Flight for 1959.

Mr. E. V. McCollum, National President SEG was an active competitor during the tournament and presented trophies and prizes to the winners following the wind up buffet dinner on Sunday night.

Mr. Norman J. Christie, Chairman of the Tournament Committee and all committee members are to be congratulated for an exceedingly well-organized and well run tournament.

C. A. COLLINS

## GUIDE FOR RECRUITING

A universally applicable guide for the recruiting of engineering college graduates has just been published by the American Society for Engineering Education.

Activities bringing together college graduates and would-be employers must meet four conditions, ASEE says:

1. To promote a wise and responsible choice of career.
2. To strengthen students' sense of integrity.
3. To develop in students an attitude of personal responsibility for their choice of career and for their success in it.

4. To minimize interference with education.

"It is in the best interest of students, colleges, and employers alike that the selection of careers be made in an objective atmosphere and complete understanding of all of the facts," according to the ASEE guide. The eight-page leaflet lists in detail recommended practices and procedures by employers, colleges, and students to assure that these ends will be achieved.

## STYLE GUIDE FOR AUTHORS

A new guide to help authors prepare clear and legible illustrations for technical papers and articles has just been approved by the American Standards Association and published by The American Society of Mechanical Engineers.

Titled American Standard Illustrations for Publications and Projection, Y15.1–1959, the 16-page illustrated pamphlet describes a standard method for preparing graphs, line drawings, and tabular illustrations for technical publications and slide projection. Additional standards providing detailed information on other specific types of illustrations are under preparation.

The standard emphasizes that simplicity, legibility, and unity are essentials of charts and graphs intended for use as visual aids with an article or speech. To help technical authors achieve these objectives, the standard presents practical guide rules and illustrates how they are used to achieve effective visual aids.

An innovation is the functional, integrated system provided for use with a standardized draft form, which is illustrated in the standard. With this, the technical author can easily prepare effective designs while saving both production time and expense.

Standard sizes for ordinary template lettering, symbols, and ruled lines are established for use with this system, or with such variations of it as may be required for non-standard drawings. Directions are included for lettering by modern electric typewriters. The standard represents the consensus of national technical societies and trade groups most concerned with the subject. Such a consensus must be established before a standard will be accepted as an American Standard by the American Standards Association, the nation's clearinghouse for voluntary standards.

The committee that prepared the standard included engineers, scientists, and graphic arts specialists representing a number of educational institutions and industrial organizations, 30-odd technical societies, and publishers.

This group was organized as a subcommittee of ASA Sectional Committee Y15 on preferred practice for the preparation of graphs, charts, and other technical illustrations, which is sponsored by The American Society of Mechanical Engineers. Chairman is Professor Douglas P. Adams of the Massachusetts Institute of Technology.

The New American Standard Y15.1 supersedes two older, obsolescent ones: American Standard Engineering and Scientific Charts for Lantern Slides, Z15.1, and American Standard Engineering and Scientific Graphs for Publications, Z15.3.

American Standard Illustrations for Publications and Projection, Y15.1-1959, is available at $2.00 a copy from the American Standards Association, 70 East 45th Street, New York 17, N. Y., or from The American Society of Mechanical Engineers, 29 West 39th Street, New York 18, N. Y.

## CALENDAR OF MEETINGS

1960

April

3–5 SEG 13th Annual Midwestern Exploration Meeting, Captain Shreve and Washington-Youree Hotels, Shreveport, La.

25–28 AAPG-SEPM Annual Meeting, Atlantic City, New Jersey.

27–30 A.G.U. Annual Meeting, Washington, D. C.

May

2–3 Society of Petroleum Engineers, AIME Wichita Falls, Texas.

October

2–5 Society of Petroleum Engineers of AIME, Fall Meeting, Denver, Colorado.

19–21 Gulf Coast Association of Geological Societies, Biloxi, Mississippi.

November

7–10 Society of Exploration Geophysicists, 30th Annual International Meeting, Moody Convention Center, Galveston, Texas.

10–12 G. S. A. Annual Meeting, Denver, Colorado.

14–16 API, Chicago, Illinois.

1961

February

19–23 AIME Annual Meeting, St. Louis, Missouri.

March

20–23 IRE National Convention, New York City.

April

24–27 AAPG-SEPM Annual Meeting, Denver, Colorado.

October

25–27 Gulf Coast Association of Geological Societies, San Antonio, Texas.

November

5–9 Society of Exploration Geophysicists, 31st Annual International Meeting, Denver, Colorado.

10–12 GSA Annual Meeting, Denver, Colorado.

13–15 API, Chicago, Illinois.

1962

March

26–29 AAPG-SEPM Annual Meeting, San Francisco, California.

26–29 IRE National Convention, New York City.

September

17–20 Society of Exploration Geophysicists, 32nd Annual International Meeting, Calgary, Alberta.

Oct. 31–Nov. 3 Gulf Coast Ass'n of Geological Societies, New Orleans, La.

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21–24 Society of Exploration Geophysicists, 33rd Annual International Meeting, New Orleans, La.

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13–16 Gulf Coast Ass'n of Geological Societies, Hot Springs, Ark.

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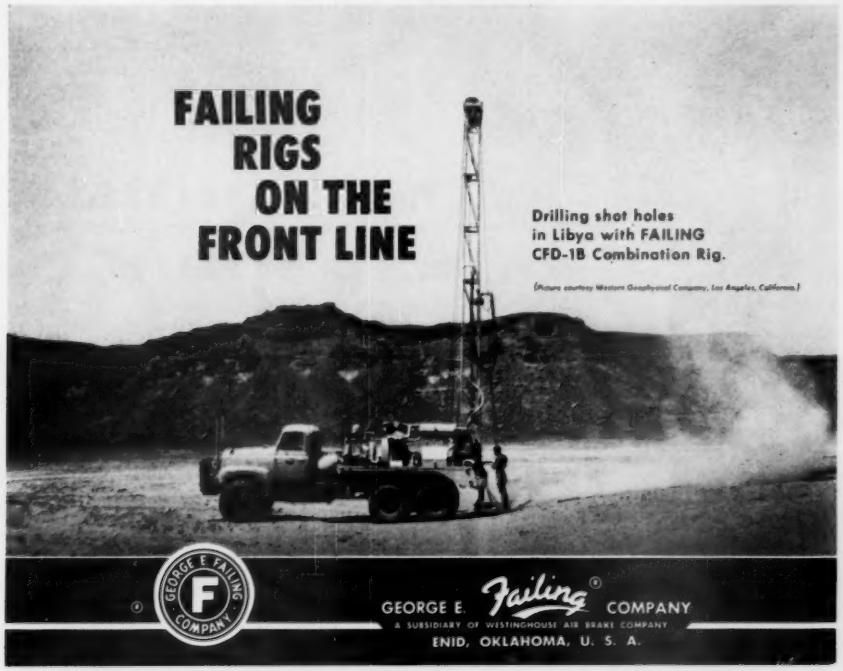
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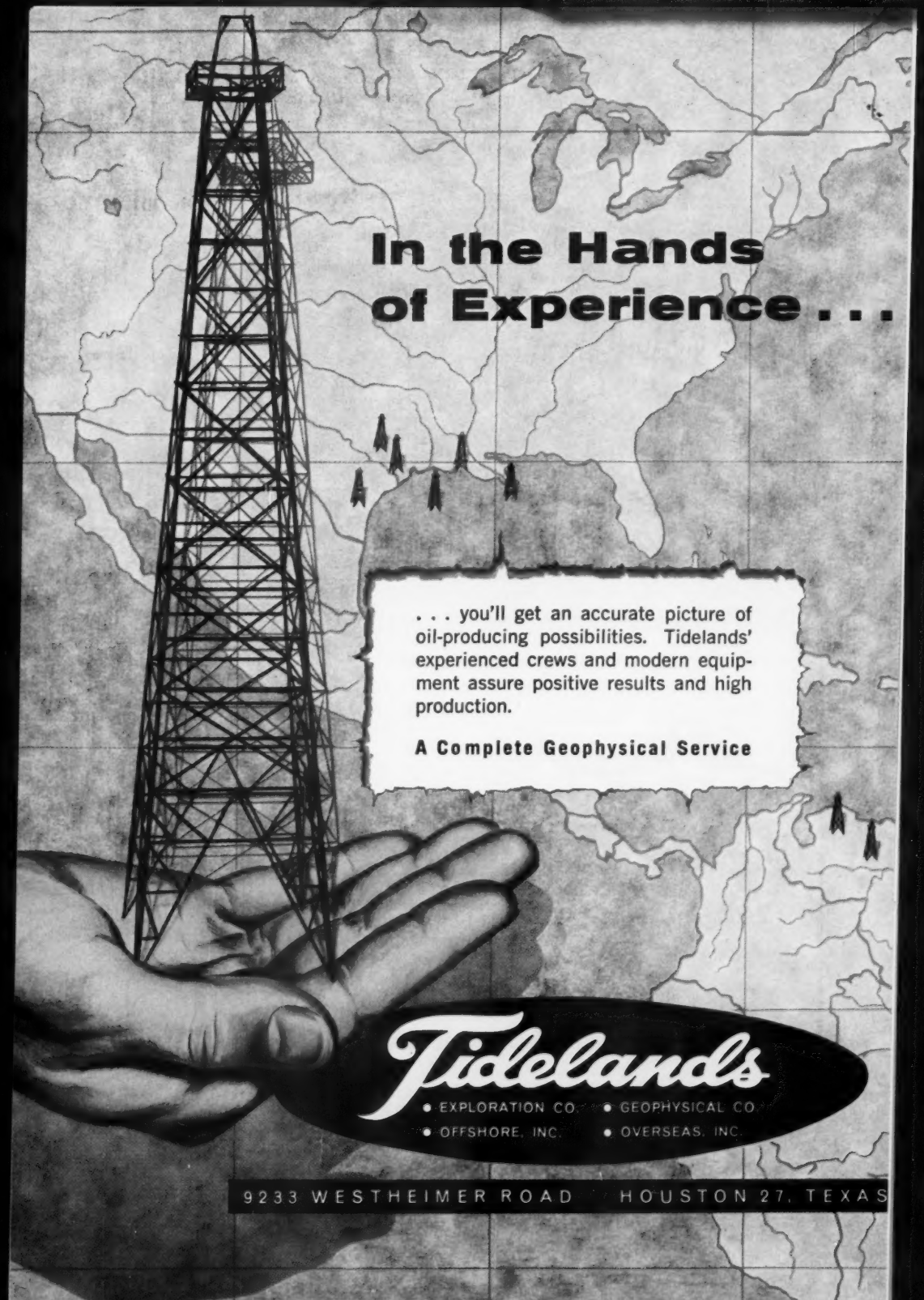
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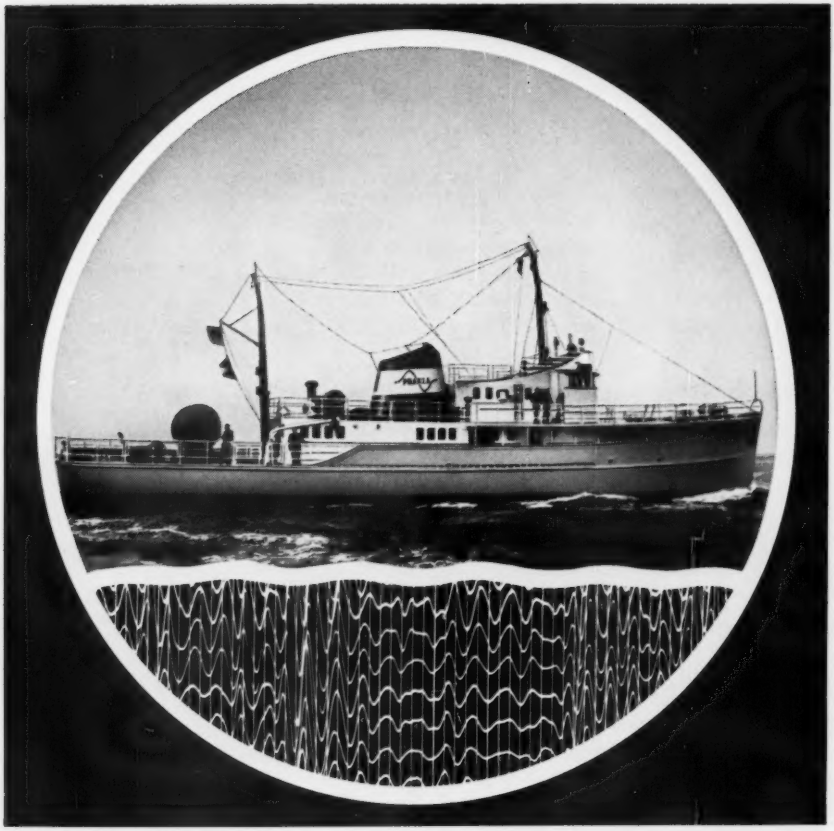

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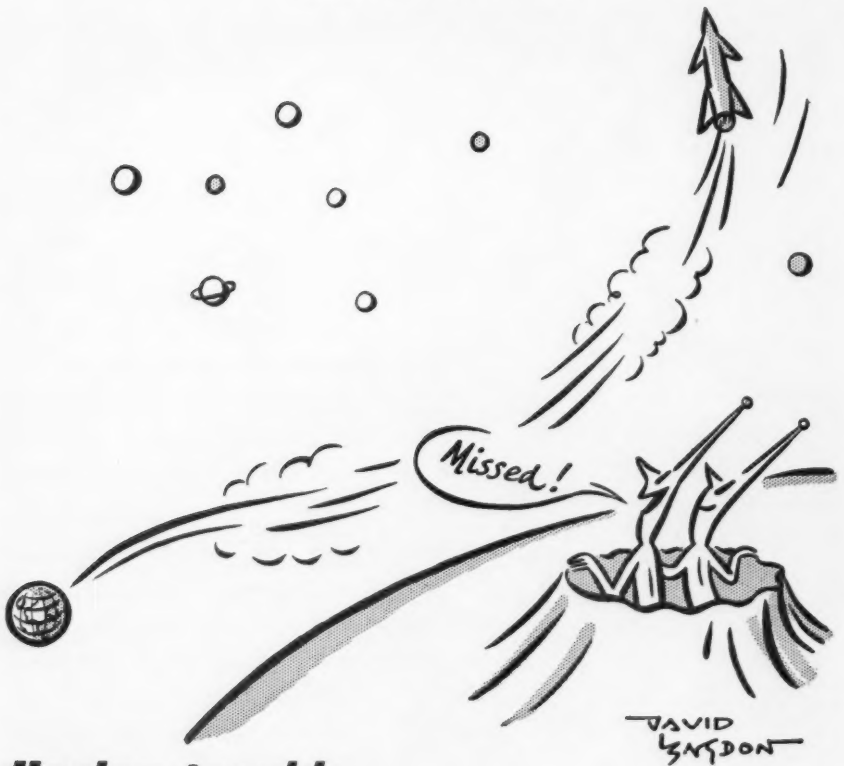


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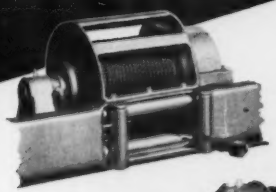

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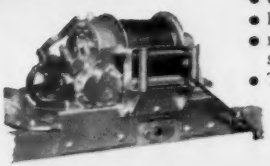

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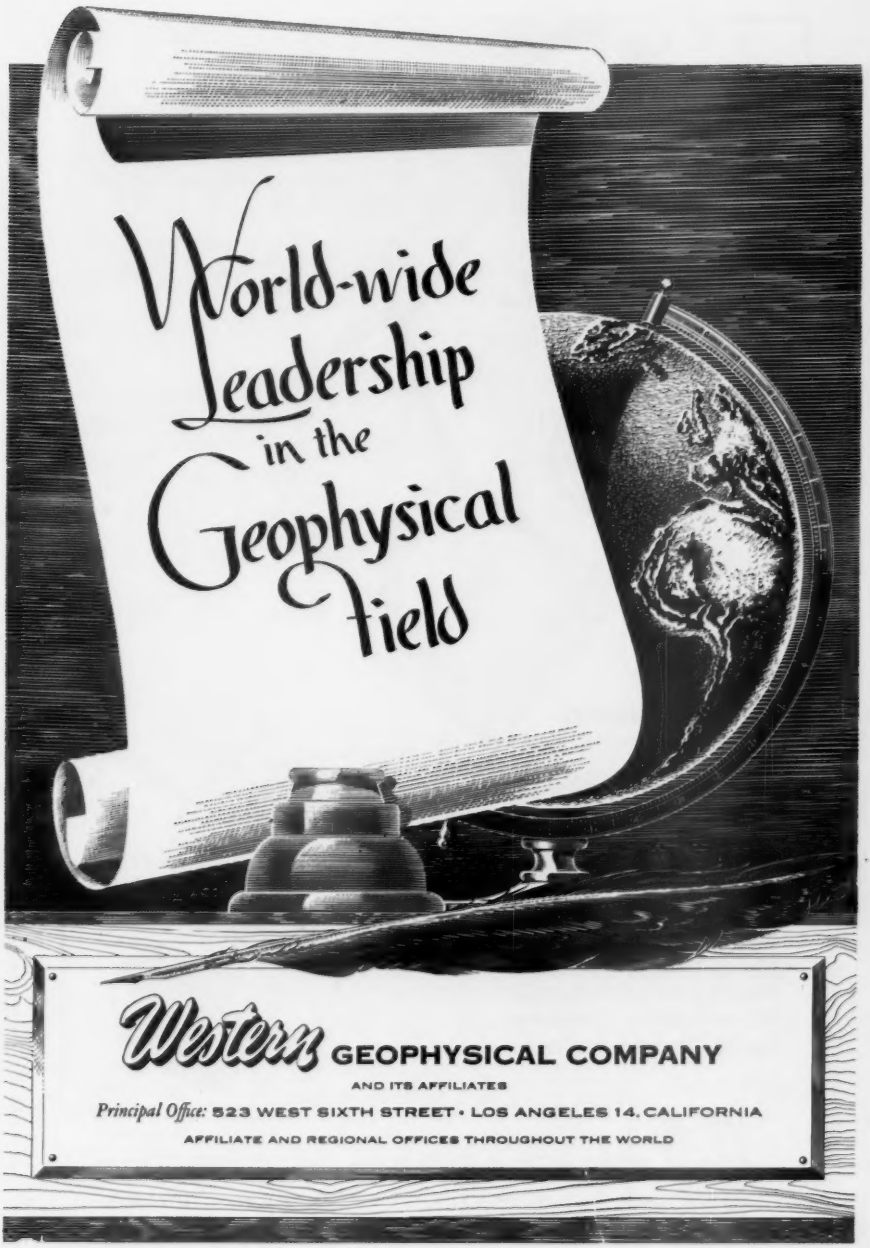
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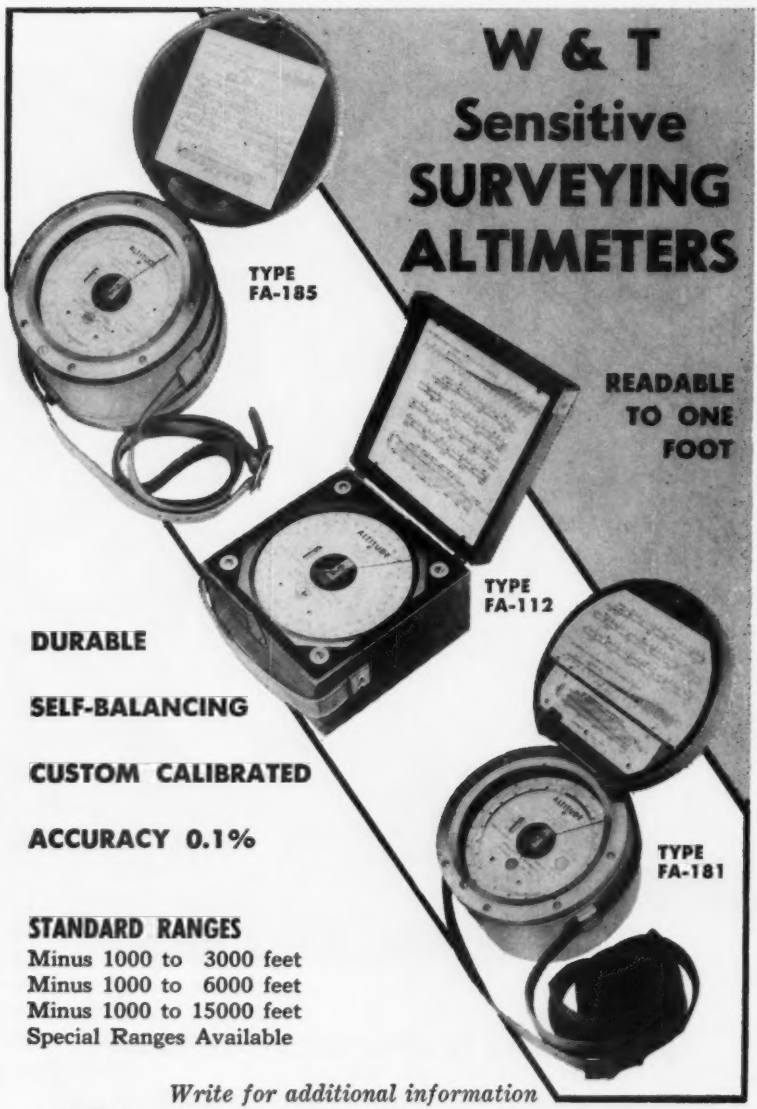


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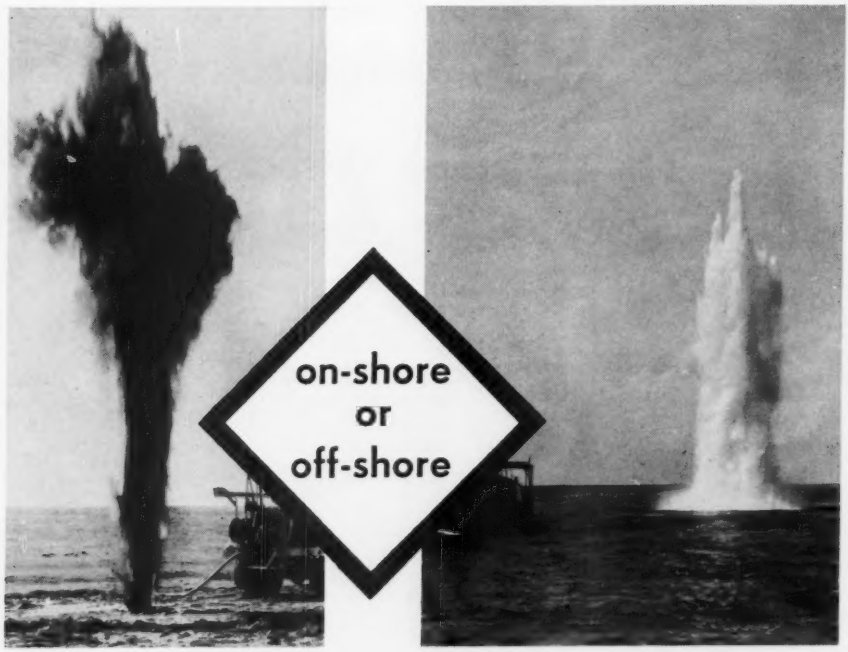


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Each to his own. Roger has to build the equipment which will funnel through pieces of film the resources, knowledge, and experience of his world-girdling company. "Zeke" Seguin has to make that film so that it will stay looking clear, clean, and reliable even though it was processed with numb fingers in a tiny closet in a truck on a frozen tundra. You can find out all about **Kodak Linagraph Survey Film** from

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(Continued from page 24)

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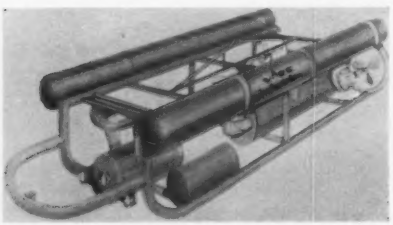
## MOBILE UNDERWATER VEHICLE

A Mobile Underwater Vehicle System has been conceived, developed and constructed by VARE INDUSTRIES of Roselle, New Jersey, in conjunction with the Department of the Navy. The system is referred to as M.U.V. Recently this system equipped with a closed circuit television camera chain was used for surveying the ocean bottom at 600 feet for site locations and cable inspection.

Operation of the underwater vehicle is remotely controlled from the console on the mother ship by means of a multi-conductor cable. This unit is propelled and guided by means of three electric propulsion motors, gear connected to propellers. The port and starboard units control the lateral motion fore and aft and also control the direction. This propulsion system is unique in that it permits the underwater vehicle to hover at any desired depth in currents or tides of several knots. This flexibility permits optimum usability of the underwater units for many and varied types of operation.



All controls are from the operator console on the mother ship. Control signals are taken to the M.U.V. and, in turn, data such as depth, propeller speed, underwater light current, TV image, etc., is displayed as data at the console.

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(Continued on page 62)

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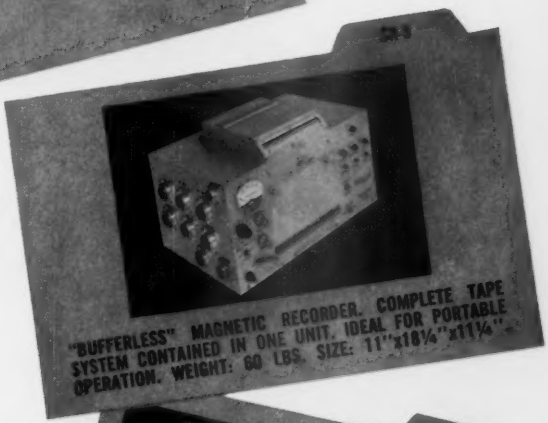

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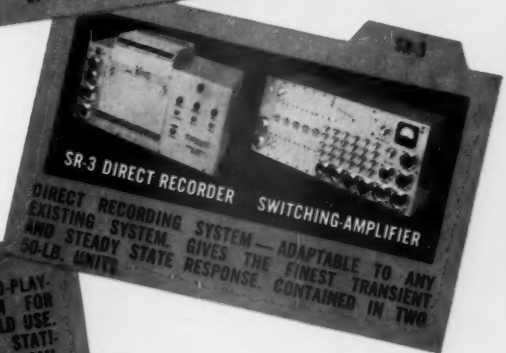

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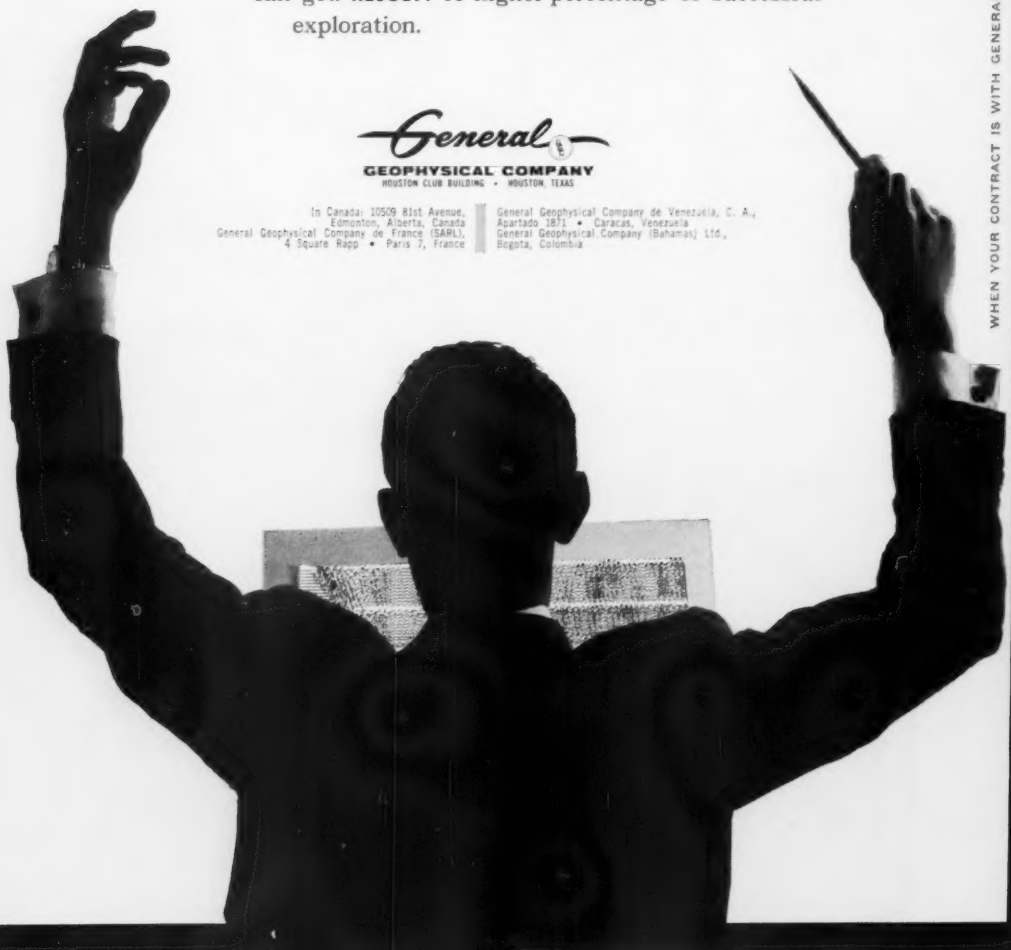

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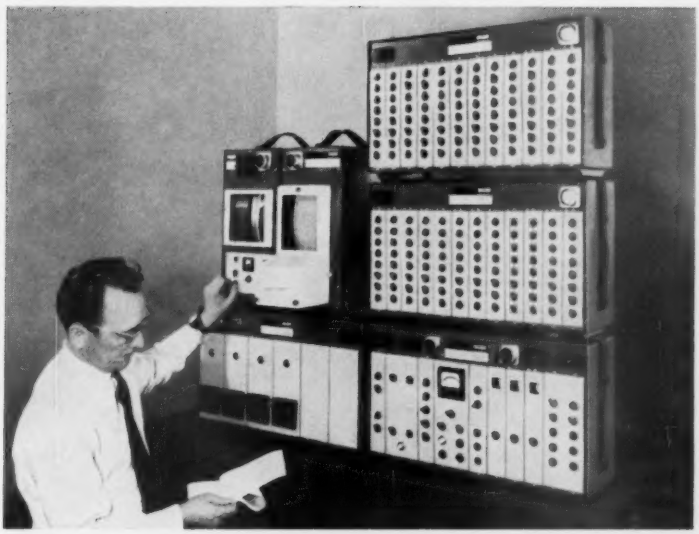

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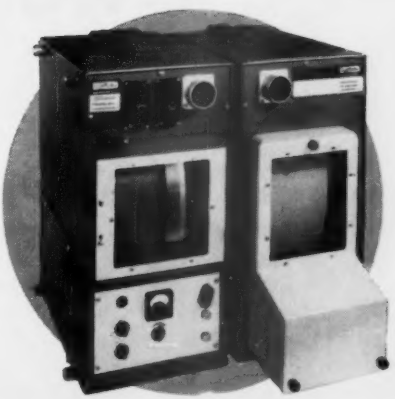

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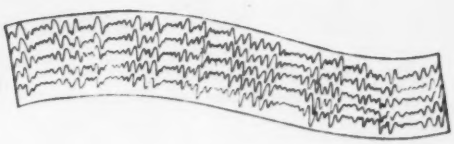

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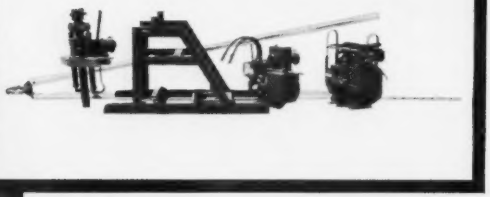

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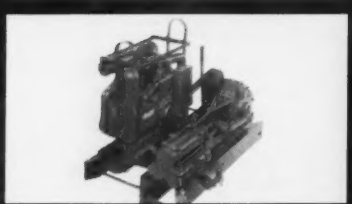

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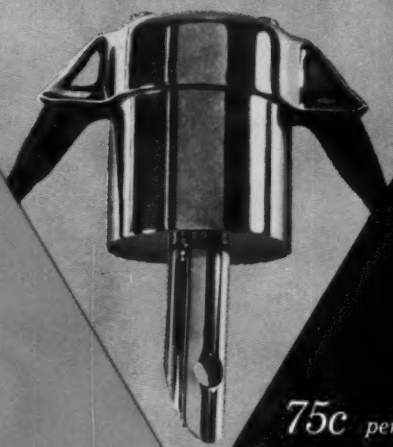
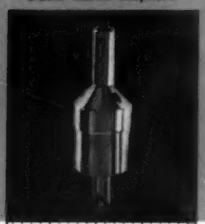
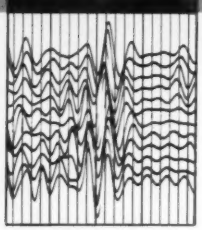


S-23M Marsh Geophone



Land (S-23) or Marsh (S-23M) . . . standard SIE high output geophones are fully guaranteed for two years!

75c *per month*
*On Lease-Purchase Plan*



An ordinary geophone and a 25 pound charge produced this record . . . NOW — the new SIE S-23 double output geophone can produce the same record with as little as 5 pounds*— save as much as 20 pounds of dynamite!

**Based on the physical relationship that amplitude of earth movement is proportional to the square root of the charge size.*

**LAND OR MARSH . . . HIGHEST SENSITIVITY OF ANY MINIATURE GEOPHONE**

An entirely new magnetic structure achieves twice the sensitivity at no increase in weight and a reduction in cost. Standard S-23's have natural frequencies of 14, 18, 21, and 28 cps – other S-23's with natural frequencies of 7 to 75 cps are also available.

Remember that SIE offers complete cabling and stringing service. Write or call for more information.

*Visit Our Geophysical Service Center*

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Phone: Chestnut 3-0132, 3-0937, 3-0964, 3-6922

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Using SIE recording supplies, Every Shot Counts, because:

- **Tapes are de-magnetized and electronically checked.**
- **Each tape individually packed and serialized.**
- **Precision ruled recording charts are guaranteed accurate to thousandths.**
- **Photographic paper and film are specially packaged to geophysical requirements, and guaranteed fresh.**
- **At $500 or more per shot, you can't take chances to save pennies. You can afford only the best — SIE.**

Call SIE — and make Every Shot Count!

***Call Eddie Nix anytime, HOmestead 5-3471 Houston (days), MOhawk 4-3765 (nights)***
***Overseas, cable SIECO, Houston.***

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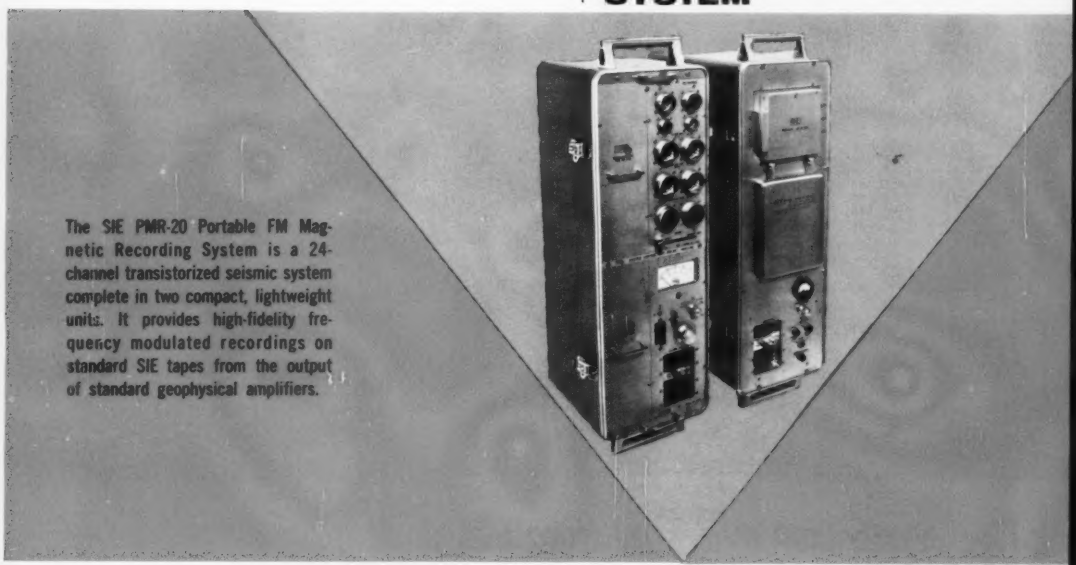
# PMR-20

## PORTABLE FM MAGNETIC RECORDING SYSTEM



**The SIE PMR-20 Portable FM Magnetic Recording System is a 24-channel transistorized seismic system complete in two compact, lightweight units. It provides high-fidelity frequency modulated recordings on standard SIE tapes from the output of standard geophysical amplifiers.**

The MR-20 transport houses the recording drum, drive system and recording heads. The modulators, demodulators, and auxiliary electronics are in the MU-20 Master Unit. Each unit contains its own transistorized power supply. In addition to the 24 seismic channels, time-break, up-hole, noise cancelling and 100 cps timing reference channels are also included. Recording and playback modulation levels are read directly from a convenient front panel meter. All record-playback switching functions are accomplished from a single front-panel switch. Movable or fixed heads can be supplied as desired. Provisions are incorporated to play back tapes through seismic amplifiers or directly through

PMR-20 FM recording provides exceptionally high signal-to-noise ratio and wide frequency response — assuring maximum reproduction fidelity comparable to no other recording method. FM also eliminates the effects of tape imperfections and irregularities. In the PMR-20, all the low noise level, low distortion, high timing accuracy characteristics of the field-proven MR-4 system are combined with additional features to produce a portable, low power drain, lightweight system of outstanding field dependability and simplicity.

### CONDENSED SPECIFICATIONS

**Channels:** 24 geophysical
4 auxiliary (Time break, up-hole, 100 cps and noise cancelling)

**Frequency response:** 1 cps to 300 cps within 1 db; 3 db down at 500 cps

**Signal-to-noise ratio:** 60 db (rms), 1 to 500 cps with noise cancelling.
54 db (rms) 20 to 200 cps without noise cancelling.
(Peak-to-peak noise averages 6-10 db higher than rms noise)

**Harmonic distortion:** Less than 1%

**Crossfeed:** Below noise level of recording system

**Relative timing accuracy:** ± 0.25ms.

**Power requirement:**

| | Standby | Operating |
|---|---|---|
| Record | 2 amp. | 7 amp. |
| Playback | 1.5 amp. | 6.5 amp. |

12 volts D.C.

**Dimensions:** MR-20 Recorder—8¼"W x 24½"H x 15"D
MU-20 Master Unit—8¼"W x 24½"H x 10½"D

**Weight:** MR-20 Recorder—60 lbs.
MU-20 Master Unit—45 lbs.

SIE
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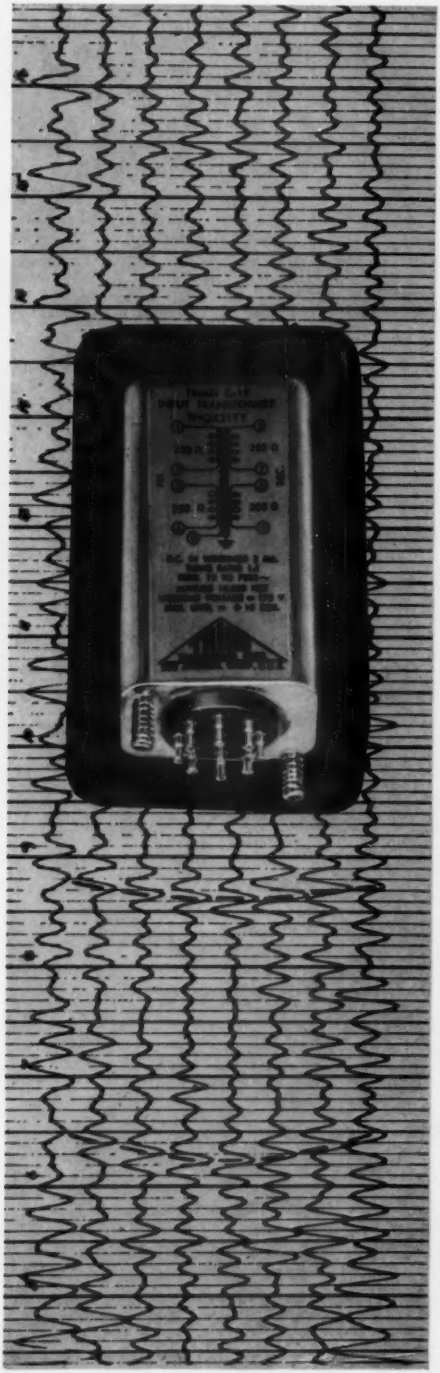

# before...
# during...
# and after

Here are three excellent reasons why designers of precision geophysical instruments specify Triad transformers:
1. Every coil on every Triad geophysical transformer is tested before impregnation.
2. Tested again during assembly.
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In addition to the Triad geophysical transformers listed in our catalog (all especially designed to meet the unique and difficult conditions of geophysical prospecting) we will supply units tailored to your specifications — at reasonable cost and in reasonable time.

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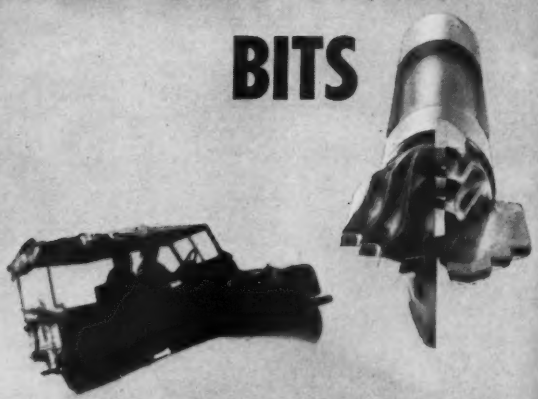
# Wherever Men Search for Oil...

## You'll find "BLUE DEMON"* BITS



With the problems of shot hole drilling pretty much the same the whole world over, it takes a bit that's as rough and tough in Tunis or Alberta . . . as in Texas or the Argentine . . . which will provide the most efficient performance at an economical per-foot cost.

Patented Hawthorne "Blue Demon" Bits have proven inherently better for international operations because:

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- Interchangeability of size and formation-type of blades in the same bit body tremendously increases bit versatility . . . reduces inventory needs . . .
- Vastly reduced bulk and weight requirements over competitive products offer additional savings in handling, shipping and storage costs . . .

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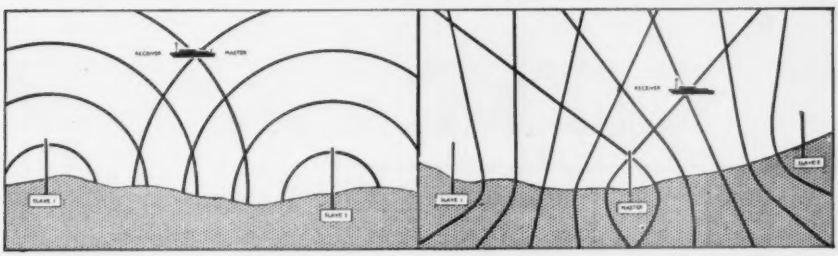
free from the bugbears of 'beat notes', modulated transmissions, multiple frequencies, reference stations, wide bandwidths and interference.

based on the sound principles and employing the same techniques as the Decca Navigator System which is now used in its basic forms by more than 6,000 vessels, to say nothing of the many survey chains throughout the world.



HI-FIX equipment can be deployed in either the **TWO RANGE** or **HYPERBOLIC** forms by deploying the master station ashore or on the survey vessel, no equipment changes being required

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*The two-range version gives the maximum accuracy obtainable from the system with only two shore stations and no lattice charts.*

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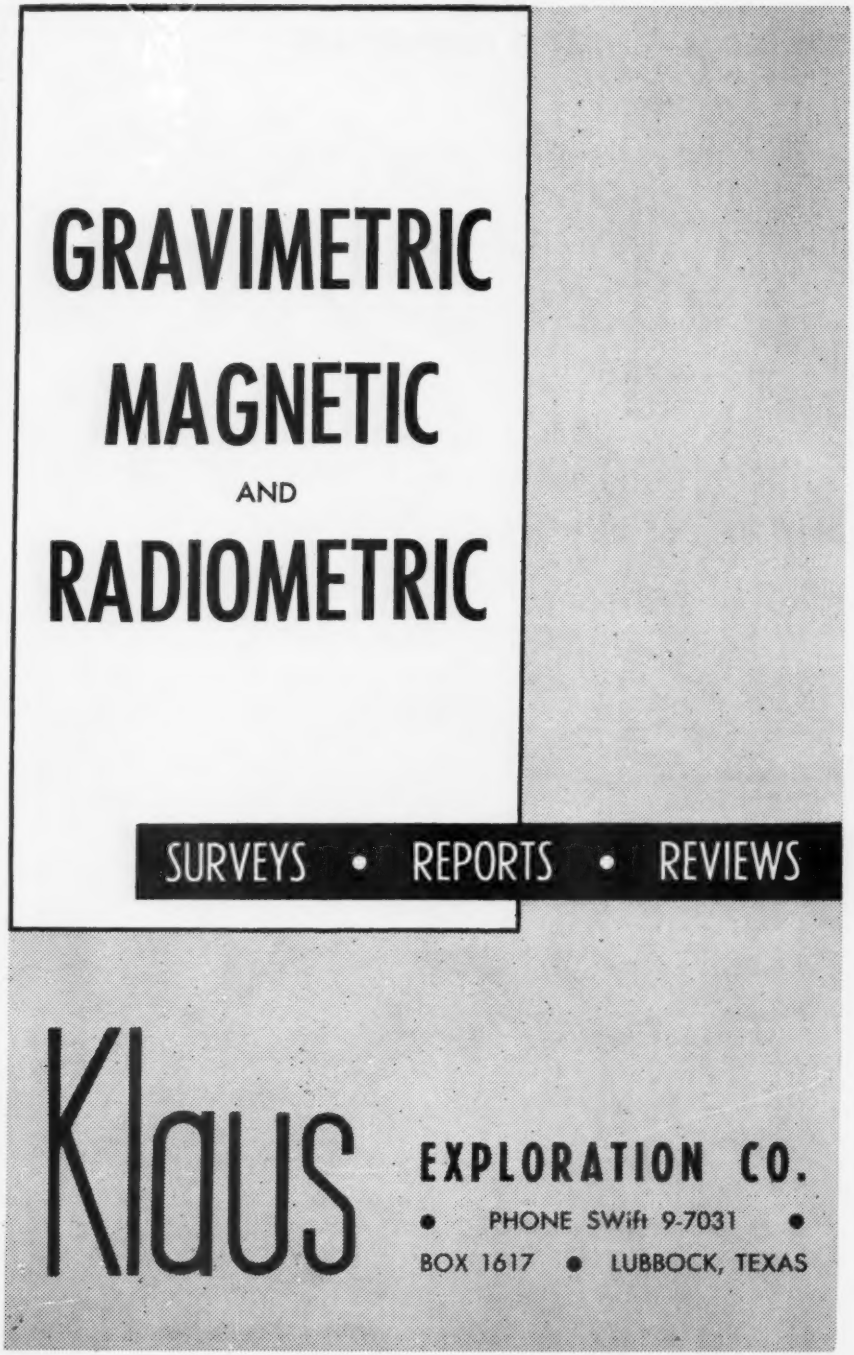
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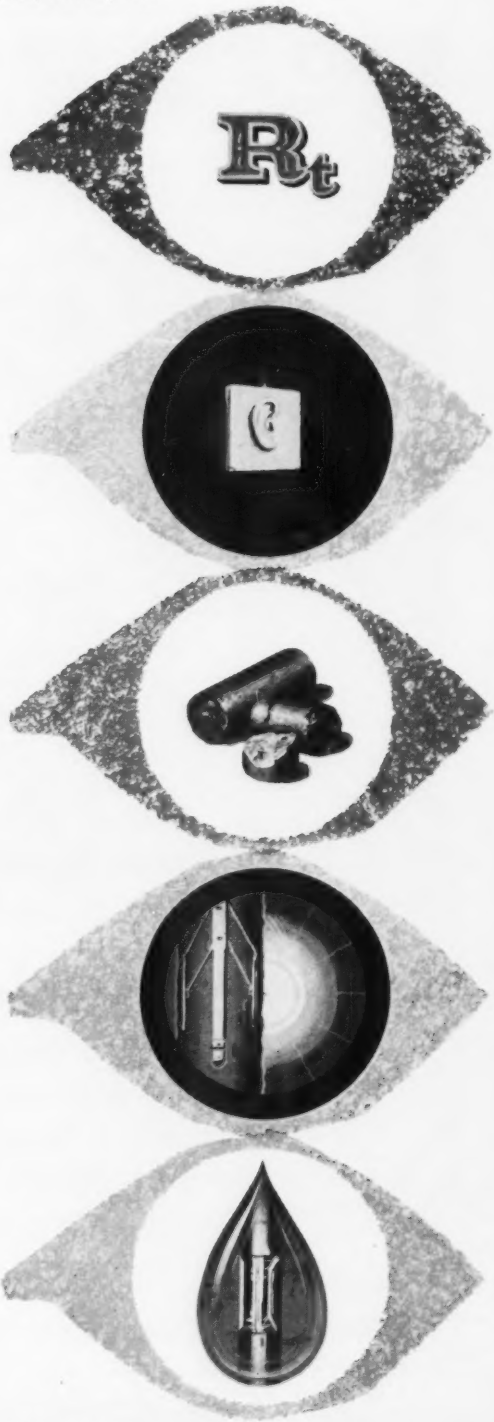

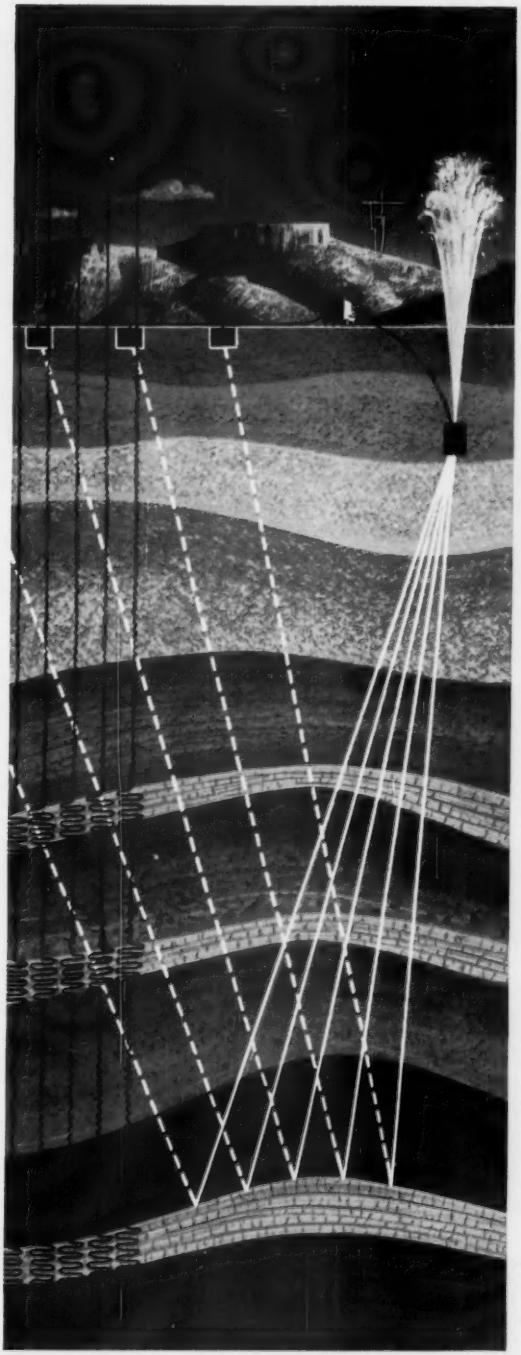

*Belt or tape—for accurate magnetic recording of seismic data ask your supplier for*

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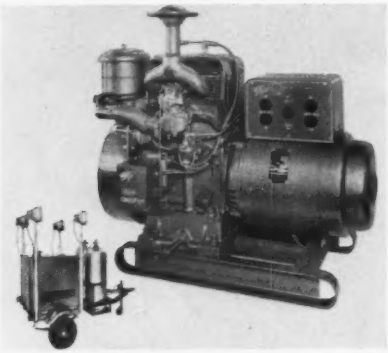
*(Continued from page 40)*

also introducing a new universal Mobil-Power trailer. In describing these heavy duty auto-type trailers, Lyman Phillips, Sales Manager, states, "the new Mobil-Power trailer is designed to meet a wide range of generator capacities, as well as alternates for housing, fuel, starting, and floodlighting. Because of their universal



design, the new Mobil-Power trailers offer many special features at low cost."

For complete detailed literature on the 705 Series Winco Engine Generators and Mobil-Power Trailers write or call **Wincharger Corporation, Sioux City 2, Iowa.**

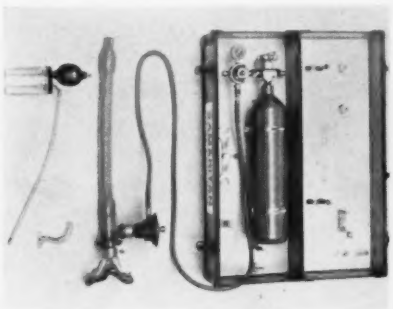
## G-22A SEISMOGRAPH SYSTEM

SIE's G-22A Seismograph System, a modern high production vehicle-mounted system useful where wide-range signal handling ability and extensive filtering flexibility are required, is described and illustrated in a bulletin. Special amplifier circuitry and control unit design provide outstanding performance with magnetic or photographic recording media, and allow selection of a variety of control factors for optimum record presentation. Magnetic recording with the G-22A System is especially effective. Outputs are provided for wide-band magnetic recording systems. AGC, non-AGC, Expander, or combined AGC-Expander operation insures complete dynamic control in any area. May be easily mounted in a cab for use on a pickup or marsh vehicle. A portable version of the G-22A (P-22) is available. **Southwestern Industrial Electronics Co., a Division of Dresser Industries, Inc., 10201 Westheimer Road, P.O. Box 22187, Houston 27, Texas.**

## RESCUE BREATHER

Globe Industries, Inc., announces the marketing of the first complete, low cost oxygen-supplied rescue breather. Named the "Samaritan," this new Globe equipment is a resuscitator-demand inhalator-aspirator.

The Samaritan, when used as an oxygen resuscitator, is not dependent on compressed oxygen as a source of power to operate a mechanical resuscitator valve. The Samaritan may be used as a Mouth-to-Mask Resuscitator for continuing resuscitation after the oxygen cylinder is depleted and if a spare oxygen cylinder is not immediately available.



The Samaritan is a breathing assistor which may be used with or without oxygen to aid people who are having difficulty in breathing caused by asthmatic attacks or other illnesses; or by the inhalation of irritating gases.

The Samaritan may be used as a demand inhalator for breathing patients after they have been resuscitated, but must be continued on oxygen. The patient receives oxygen at the rate he "demands."

The Samaritan also includes an aspirator to remove fluids, vomitus and mucous from the mouth and upper throat. The Samaritan is easy to carry, weighing only 26 pounds complete with fully charged cylinder.

For complete information and illustrated instruction card and catalog sheet write **Globe Industries, Inc., 125 Sunrise Place, Dayton 7, Ohio.**

## NEW AN PELLETS

Ammonium nitrate in a new pellet form said to increase the economy and effectiveness of AN blasting is announced by the

*(Continued on page 69)*

# Report from Rogers

The true value of the final, the complete geophysical report stems from many mechanics, many techniques, many interpretations that follow the first survey. The final Rogers Geophysical Report is an *expert* and thus *complete* analysis of the known and unknown of your potential oil province. That is because the expertness of Rogers extends to all the vital links between the Report and the first planning. Completeness and expertness are Rogers' bywords in geophysical prospecting.

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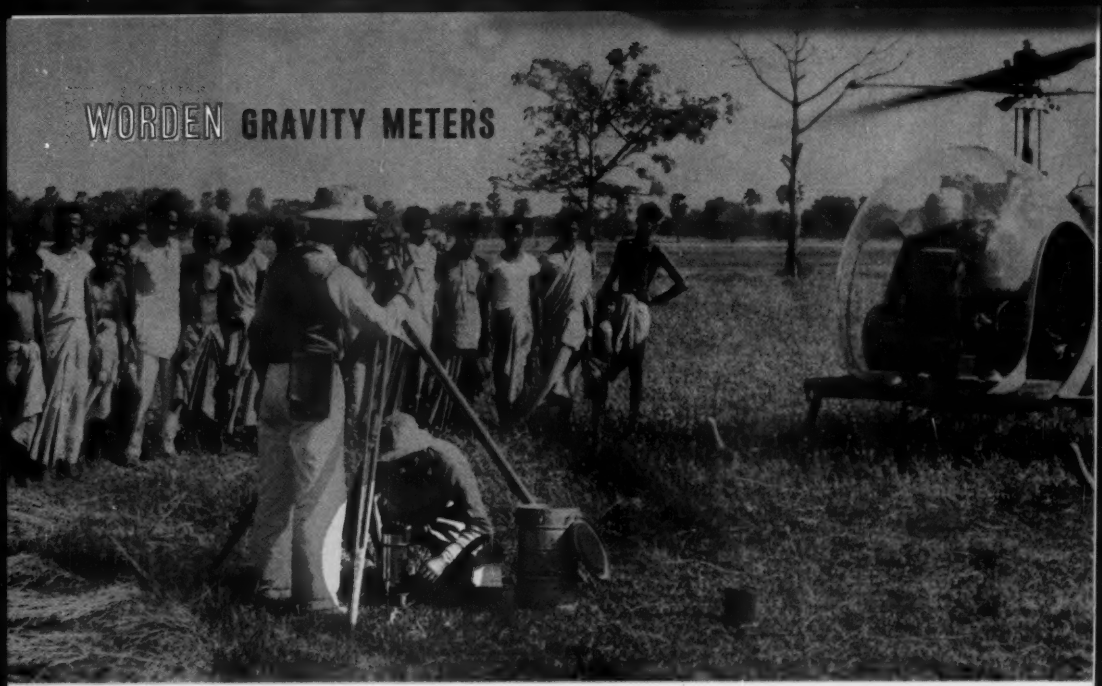


# Take a NEW READING ON GRAVITY as an Effective, Economical Exploration Method

If you have not used Gravity, or if your use has been limited in recent years, it will pay you to reappraise the benefits of this fast, low cost exploration method. Instrumentation, operational techniques, and interpretation have been greatly improved enabling many operators to provide *specific and detailed* geologic information. Originally, the Gravity Method was thought of primarily as a means of determining *salt dome configurations*. Now, stratigraphic and structural information can be obtained such as: the areal extent and configuration of sedimentary basins; the maximum thickness and variation in thickness of basin sediments; regional structures within the basins; local and regional fault systems, including horsts and grabens, within the section; and local and regional thrust faults.

To obtain the best results, use the world's most proved gravity instrumentation . . .

**There's a *WORDEN* Meter for Every Land Application**

The MASTER and PROSPECTOR model *WORDEN* Gravity Meters provide the most demanding operating specifications ever achieved in portable meters. They retain the true portability and flexibility of the quartz element design plus the exclusive "Universal Compensation" feature which extends the temperature compensated range up to 6600 mgls. (world coverage). The MASTER is distinguished from the PROSPECTOR by a low power Temperature Stabilizer, which maintains a nearly constant internal temperature in spite of extreme outside thermal shocks. Both meters are available in Standard and Geodetic models.

The PIONEER is ideally suited for gravity programs in areas of limited latitude and temperature variations and where the need for less frequent base ties exists. Also available in Geodetic model.

The EDUCATOR gravity meter is intended to meet the needs of educational or training programs where the required tolerances are much wider than for commercial programs.

**Specifications for the respective *WORDEN* Gravity Meters are shown at right . . . contact TI's Gravity Department for additional information.**

**Select Your *Worden* Gravity Meter from the widest combination of models and ranges in the industry!**

| When requesting a quotation, copy the specification categories in this column and specify the values desired from those found under the respective meters. | the *Master* | the *Prospector* | the *Pioneer* | the *Educator* |
|---|---|---|---|---|
| Minimum Recommended Operating Range—Specify to nearest 100 mgls.* plus latitude and elevation indication | 3000 mgls. | 3000 mgls. | 2400 mgls. | Limited . . . Will be at least 1600 mgls. |
| Minimum Total Operating Range (Reset) —Specify to nearest 100 mgls.* | 5200 mgls. | 5200 mgls. | 4000 mgls. | Limited . . . Will be at least 2000 mgls. |
| Small Dial Range | 800 Dial Divisions x Small Dial Constant (2200 on Special Order) | 800 Dial Divisions x Small Dial Constant (2200 on Special Order) | 800 Dial Divisions x Small Dial Constant | 800 Dial Divisions x Small Dial Constant |
| Small Dial Constant—Specify constant desired* | Standard .08 to .11 mgl./Dial Division (From 0.05-1.00 also available) | Standard .08 to .11 mgl./Dial Division (From 0.05-1.00 also available) | Standard .08 to .11 mgl./Dial Division (From 0.05-1.00 also available) | 0.10-1.00 mgl./ Dial Division |
| Small Dial Calibration Linearity over full range | 1 part in 1000 | 1 part in 1000 | 1 part in 1000 | 1 part in 1000 |
| Small Dial Reading Accuracy | 0.1 of Small Dial Division | 0.1 of Small Dial Division | 0.1 of Small Dial Division | 0.1 of Small Dial Division |
| External Temperature Control | Temp. Stabilizer requires 1.00 watts power for a 100° F. differential. Four Rechargeable "D" Size Batteries maintain 90° F. differential for 10 hours and are mounted in removable pack on side of meter. Any 4.5 to 12 volt DC source may be substituted. | None | None | None |
| Small Dial Mechanism | Self counting, read from top and directly coupled (no gears for backlash) with screw which contacts quartz measuring spring. | | Side and top reading, directly coupled (no gears for backlash) with screw which contacts quartz measuring spring. | |
| Large Dial Range — Specify range desired* | 800 Dial Divisions x Large Dial Constant | | | Geodetics not available |
| Large Dial Constant | Standard 6.5 to 12.0 mgls./D.D. | | | Geodetics not available |
| Large Dial Calibration over full range (8 turns) | Curve furnished with values accurate to one part in 1000—measured over full range (8 turns). | | | Geodetics not available |
| Size, Inches: Diameter Height | 7" 14" | 7" 14" | 5½" 10½" | 5½" 10½" |
| Weight, Pounds: Net Including carrying case | 9¾ lbs. 18 lbs. | 7½ lbs. 15¾ lbs. | 5⅛ lbs. 12 lbs. | 5⅛ lbs. 12 lbs. |
| *Price of meter is determined mostly by the Ranges and Dial Constant Specified. | | | | |

***Write for Bulletin No. GM-206***

***WORDEN* Gravity Meters Are Made Exclusively By**

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**Type Gf6**
**after Schmidt**

Field proven for decades
In actual use throughout the world
Reading accuracy: up to 1 gamma
Direct measuring range: 1200 gamma
Magnet Systems for vertical and horizontal components
Also suitable for recording of the magnetic variations

# *Precision Magnetometers*

**Type Gfz**

for measuring the vertical component
Easy to operate and time saving only 40 sec. per measuring station
Reading accuracy: better than 2 gamma
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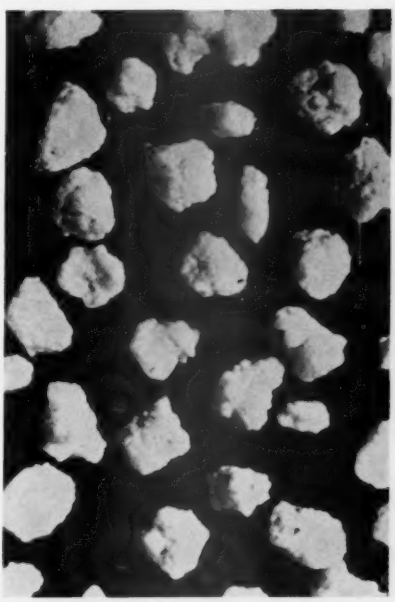

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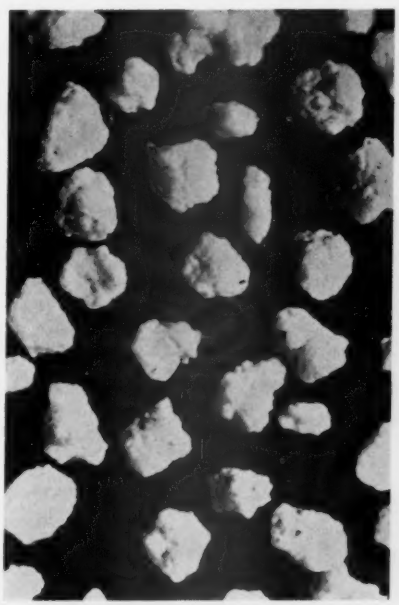

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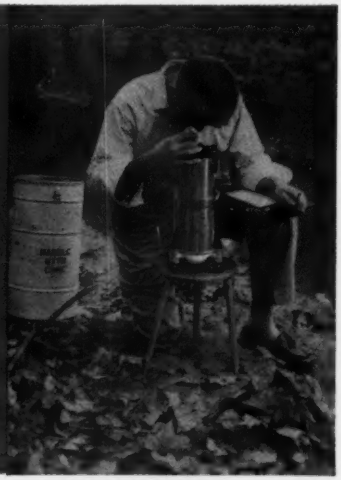

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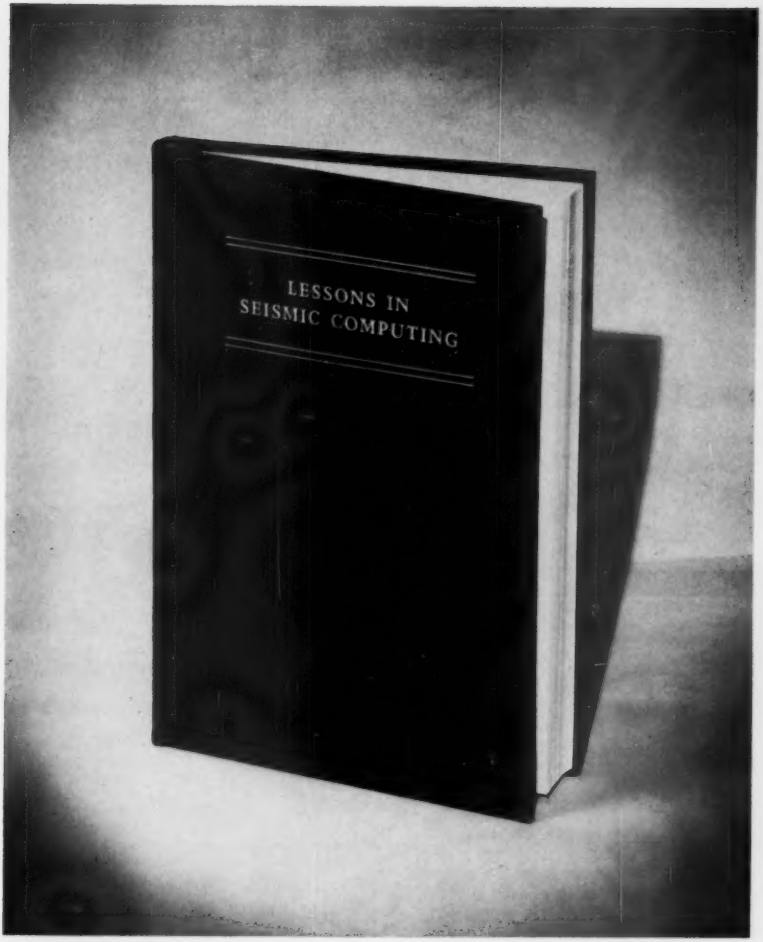


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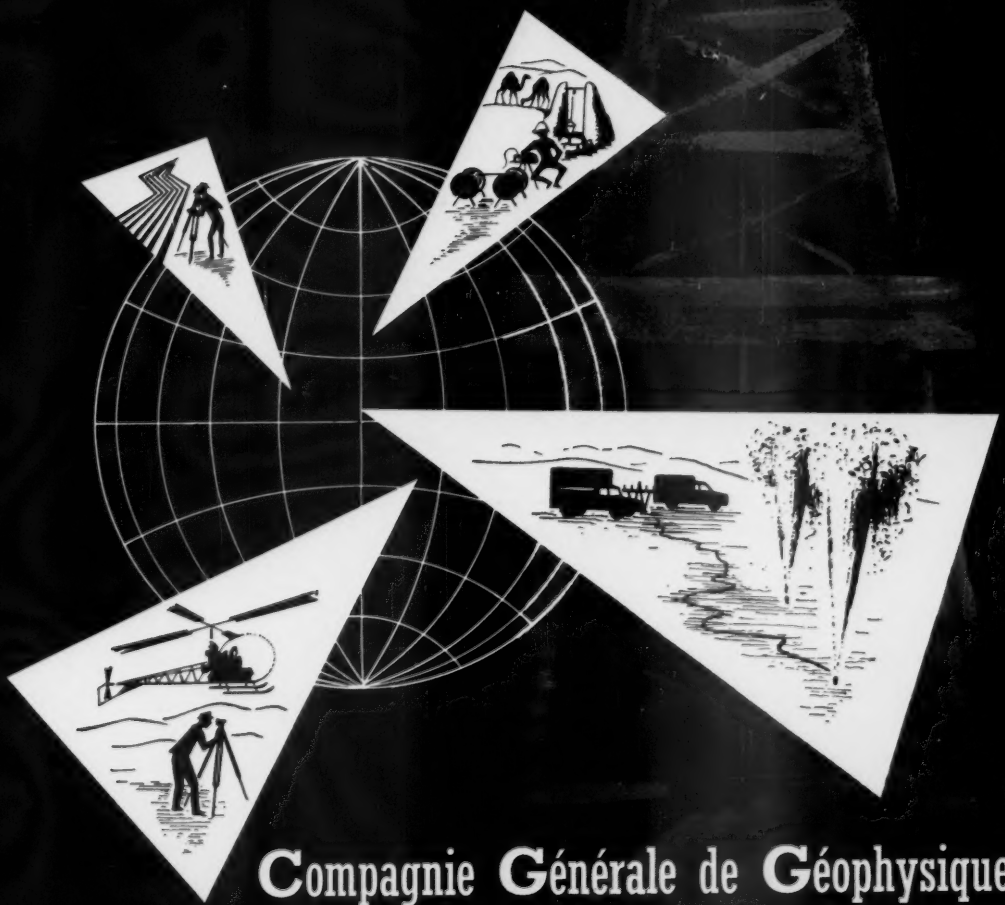

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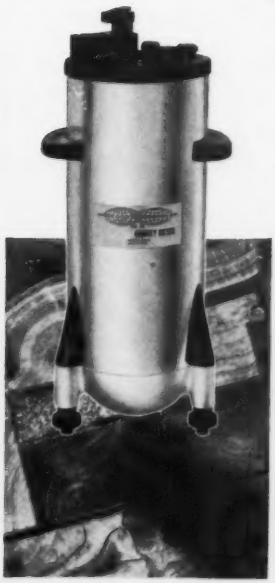

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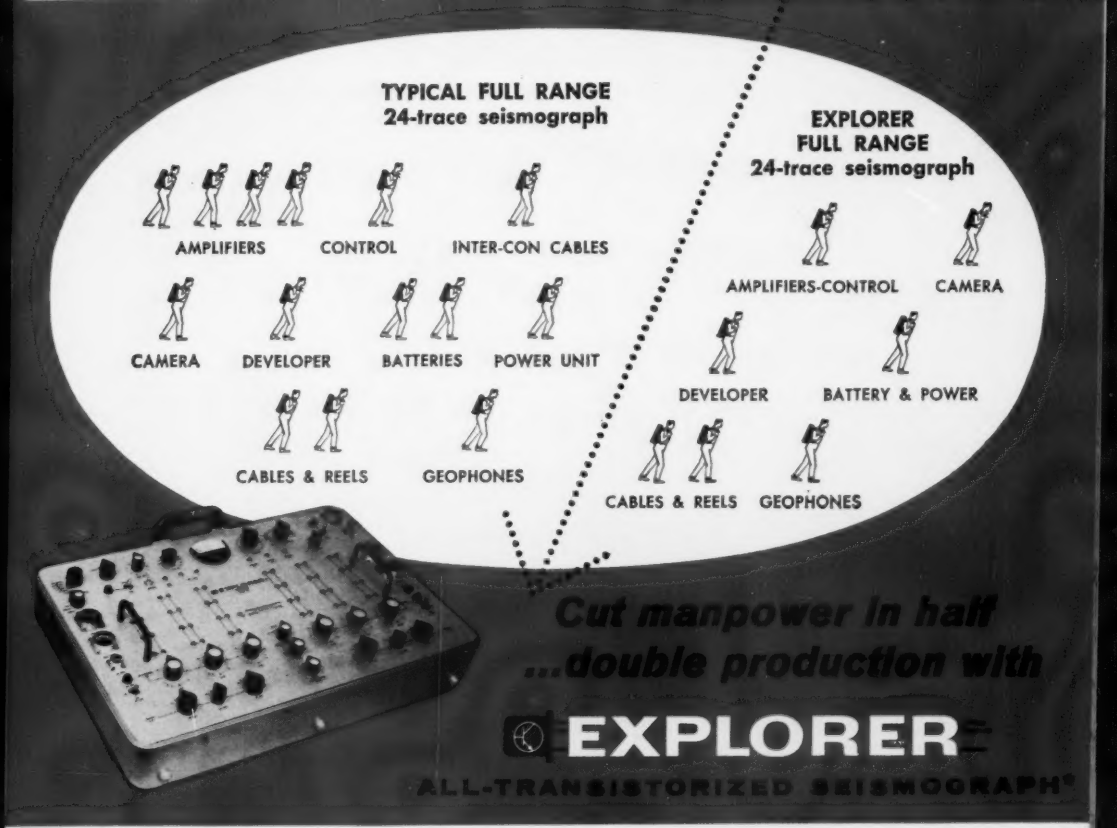


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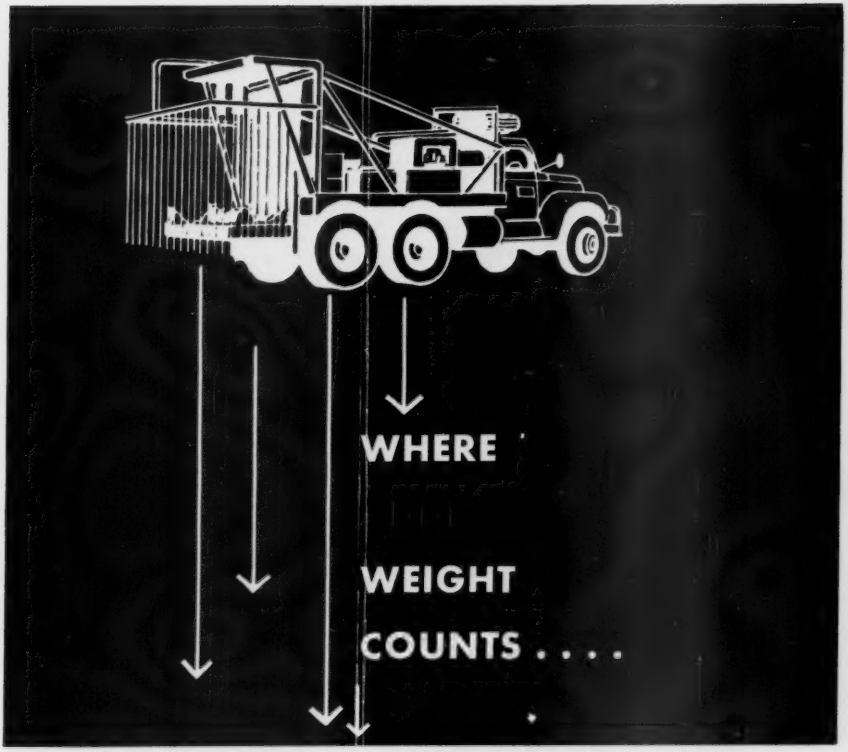


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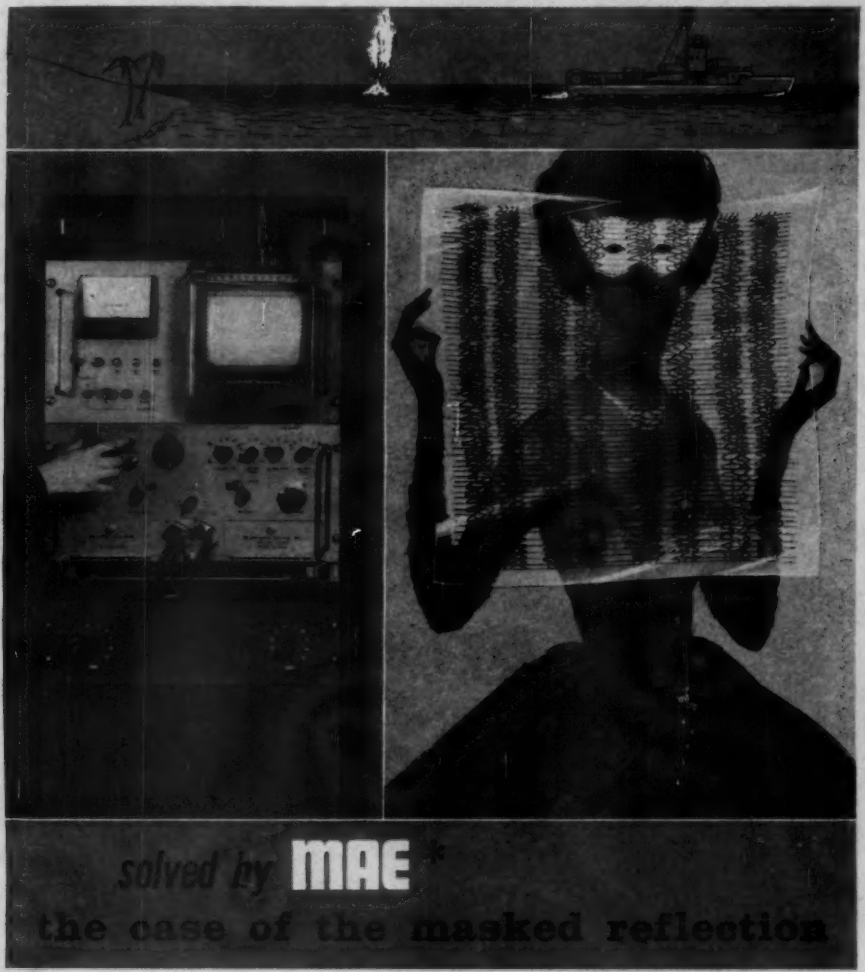


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